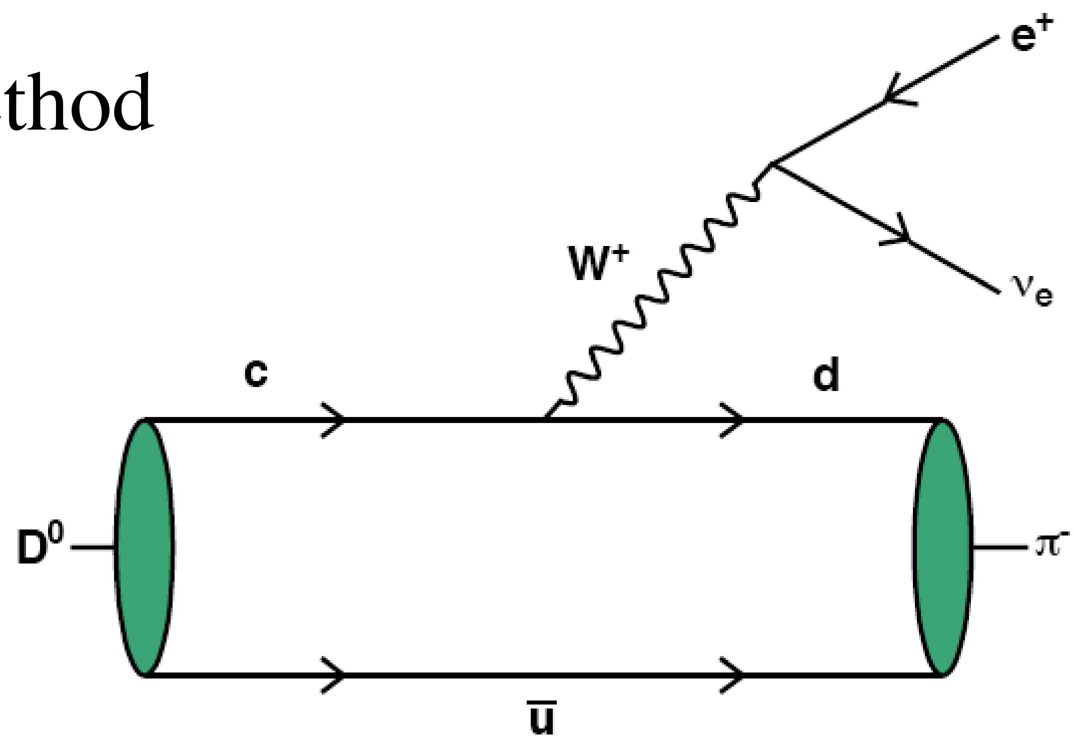
A Study of the Semileptonic Charm Decays $D^0 \to \pi^- e^+ \nu$, $D^0 \to K^- e^+ \nu$, $D^+ \to \pi^0 e^+ \nu$ and $D^+ \to \overline{K}^0 e^+ \nu$

CORNELL UNIVERSITY LEPP

LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

Outline

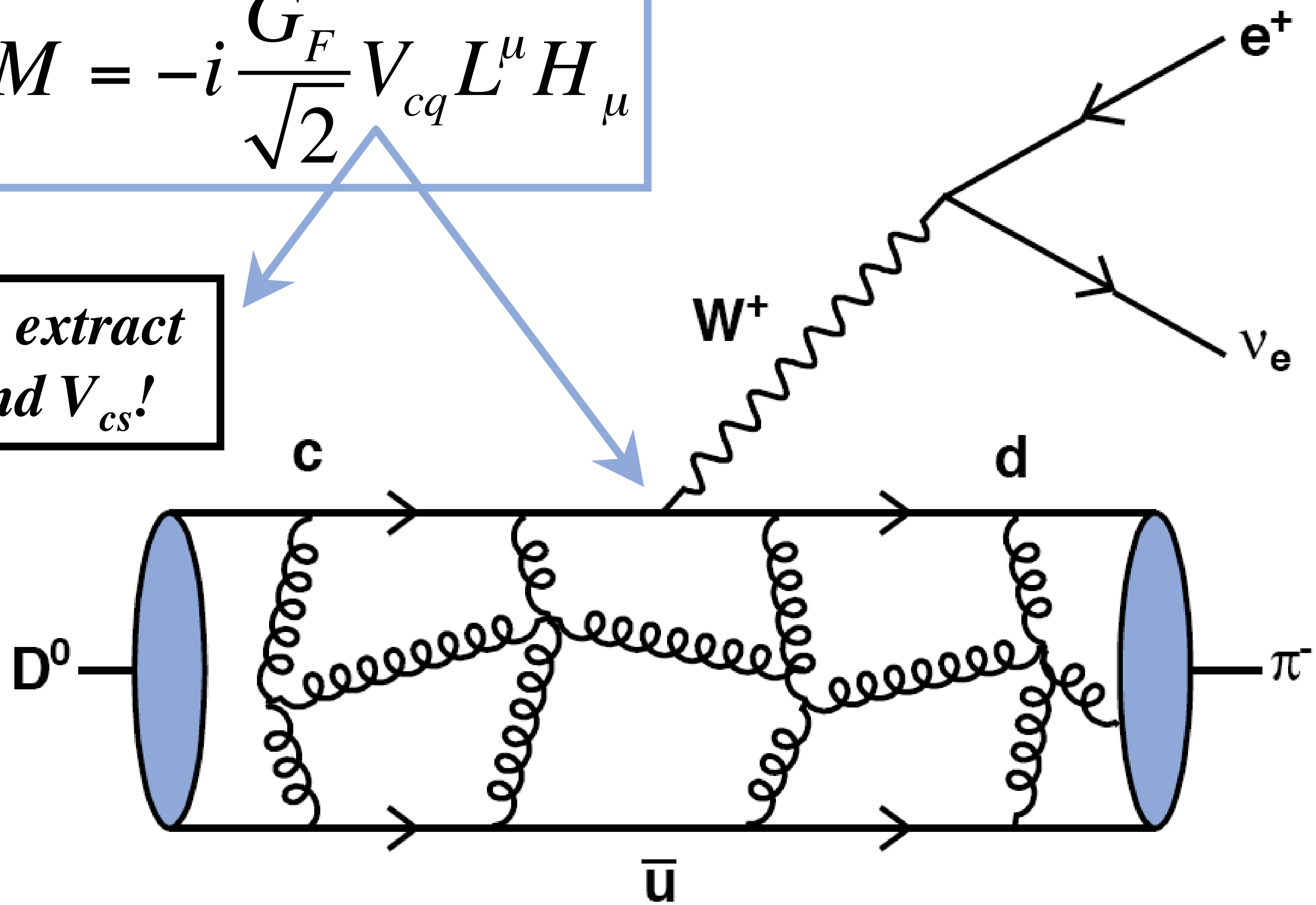
- Motivation & Theory
- Analysis Method
- Results
- Summary



Semileptonic Decays

$$M = -i\frac{G_F}{\sqrt{2}}V_{cq}L^{\mu}H_{\mu}$$

We can extract V_{cd} and V_{cs}!



Pseudoscalar SL Decays: D → Peν

$$L^{\mu} = \bar{u}_e \gamma^{\mu}(1-\gamma_5)v_{\nu}$$

Easy to calculate!

$$H_{\mu} = \langle P(p)|\bar{q}\gamma_{\mu}c|D(p')\rangle$$

Difficult to calculate, because of strong gluon interactions.

Parameterize H_{μ} with Form Factors!

$$H_{\mu} = f_{+}(q^2)(p'+p)_{\mu} + f_{-}(q^2)(p'-p)_{\mu}$$

Four vector of the virtual W boson

$$q^{\mu} = (p'-p)^{\mu}$$

Only two independent four vectors.

Differential Decay Width

In the limit of zero electron mass only a single form factor is required:

$$\left(\frac{m_e}{M_D}\right)^2 \to 0 \quad \Rightarrow \quad q^\mu L_\mu = 0$$

$$\boxed{\frac{d\Gamma(D \to Pe\nu)}{dq^2} = \frac{G_F^2 \left|V_{cq}\right|^2}{24\pi^3} p^3 \left|f_+(q^2)\right|^2}$$

Pseudoscalar semileptonic decays give us access to *form factors* and *CKM matrix elements*.

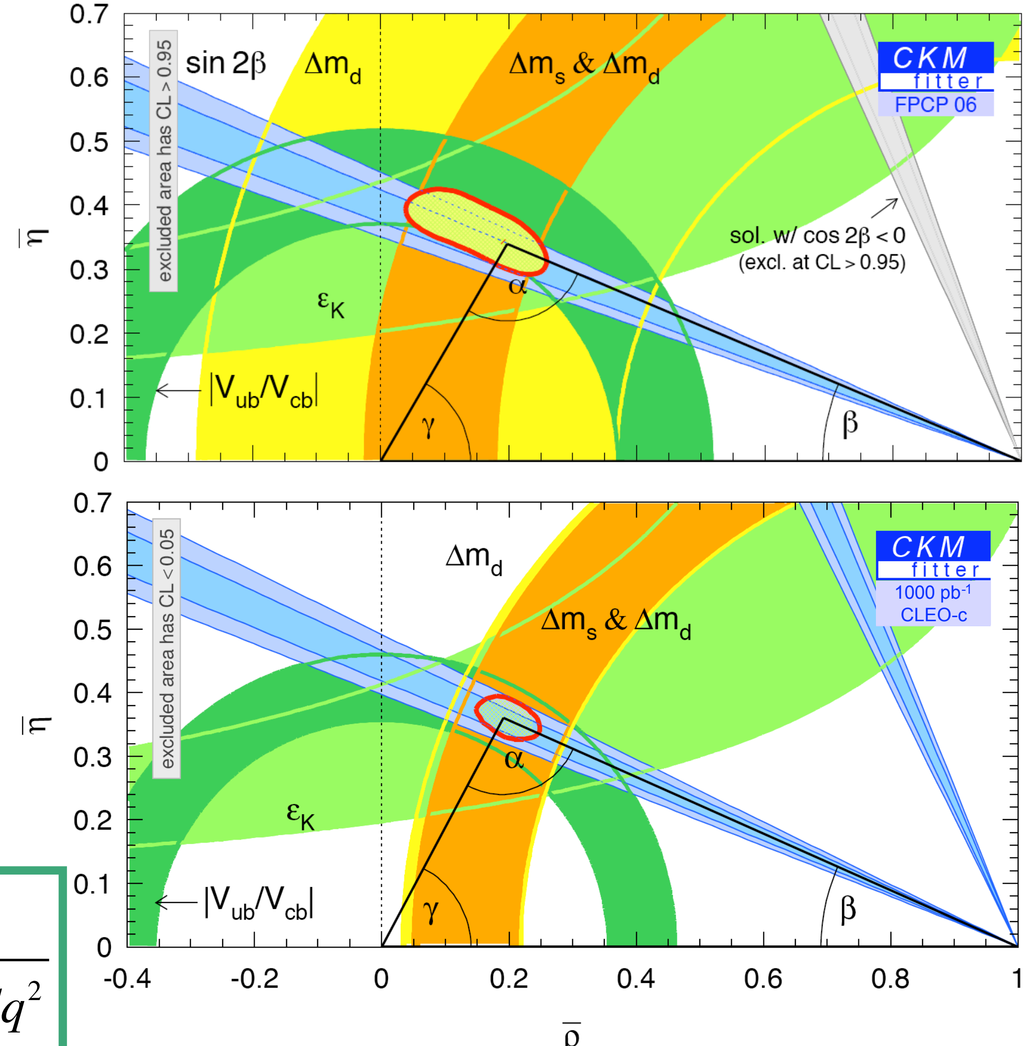
Why are these things important?
Why Charm?
How can we calculate form factors to get CKM?

CKM & Unitarity Triangle

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- *CLEO-c measurements give confidence in high precision lattice results.*
- *Measurement of semileptonic form factors.*
- *Ratios of leptonic to semileptonic - no CKM element reliance!*

$$\frac{\Gamma\left(D^{+} \to \mu^{+}\nu_{\mu}\right)}{\Gamma\left(D^{0(+)} \to \pi^{-(0)}e^{+}\nu\right)} \propto \frac{\left|V_{cd}\right|^{2} f_{D^{+}}^{2}}{\left|V_{cd}\right|^{2} \int \left|f_{+}(q^{2})\right|^{2} dq^{2}}$$

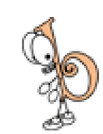


Why Charm?

The study of charm semileptonic decays at CLEO-c is important because:

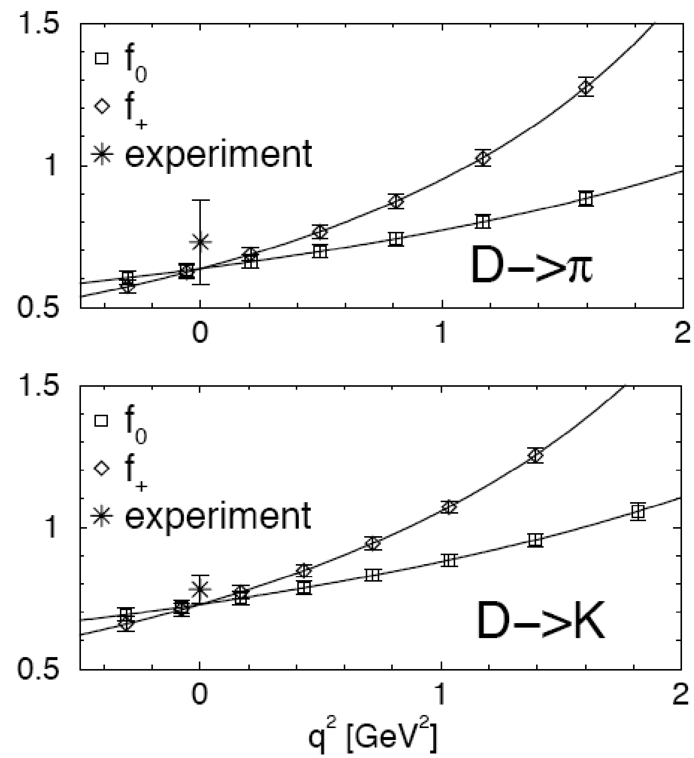
The CKM matrix elements V_{cs} and V_{cd} can be extracted from branching fraction results. These measurements contribute directly to constraints on the CKM matrix!

We can measuring branching fractions in multiple q^2 ranges. Using the relatively well known charm CKM matrix elements allows us to measure the form factors $f_+(q^2)$ with few percent precision.



Form Factors - Motivation

- In recent times lattice QCD calculations have undergone significant improvements.
- **<u>Few percent level</u>** results for semileptonic form factors are expected for summer 2006.
- Branching fraction and form factor measurements from experiment at the same precision (or better) can verify these results for charm.



Phys. Rev. Lett. 94, 011601 (2005)

Form Factors

Reminder $\longrightarrow$

$$\boxed{\frac{d\Gamma(D \to Pe\nu)}{dq^2} = \frac{G_F^2 \left|V_{cq}\right|^2}{24\pi^3} p^3 \left|f_+(q^2)\right|^2}$$

What do we know about form factors?
They can be parameterized with a general dispersion relation.

$$f_+(q^2) = \frac{f_+(0)}{1-\alpha} \frac{1}{1 - q^2 / m_{pole}^2} + \frac{1}{\pi} \int_{(M_D+m)^2}^{\infty} dq'^2 \frac{\mathrm{Im}(f(q'^2))}{q'^2 - q^2}$$

Complaint: This form is too general … doesn't nail down the dynamics of the semileptonic decays!

Q: Can we use the dominance of the pole just above threshold (for heavy-to-light decay, not quite for D → π) to make a simpler description that will predict the dynamics of our decays?

Simple Pole Model - Ruled Out!

The simplest approach - can we describe the data with JUST the distinct pole?

$$D \to \pi$$
$$m_{pole} = M_{D_s}$$

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2 / m_{pole}^2\right)}$$

Simple Pole Model

$$D \to K$$
$$m_{pole} = M_{D_s^*}$$

$$\boxed{\mathbf{D \to K}}$$

$$\boxed{M_{D_s^*} = 2.112 GeV}$$

E687 1995	$1.87^{+0.11+0.07}_{-0.08-0.06}$
CLEOIII 2005	$1.89 \pm 0.05^{+0.04}_{-0.02}$
FOCUS 2005	$1.93 \pm 0.05 \pm 0.03$
Babar 2006	$1.854 \pm 0.016 \pm 0.020$

Ruled out by recent experiments at the several sigma level!

Modified Pole Model - Ruled Out!

Can we incorporate some of the effective poles from the continuum using a single parameter?

Assumption:
Scaling violations $\beta \sim 1$,
Spectator interactions $\delta \sim 0$

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m^2_{pole}\right)\left(1 - \alpha\, q^2/m^2_{pole}\right)}$$

Modified Pole Model

$$1 + 1/\beta - \delta \equiv \frac{(M_D^2 - m_{K(\pi)}^2)}{f_+(0)} \left.\frac{df_+}{dq^2}\right|_{q^2=0} \approx 2$$

(Becher and Hill)

$\boxed{\mathbf{D \rightarrow K}}$

Experiment	α	*1 + 1/β - δ*
CLEOIII 2005	$0.36 \pm 0.10^{+0.03}_{-0.07}$	0.99
FOCUS 2005	$0.28 \pm 0.08 \pm 0.07$	0.93
Belle 2006	$0.40 \pm 0.12 \pm 0.09$	1.01
Babar 2006	$0.43 \pm 0.03 \pm 0.04$	1.04

Series Parameterization

Becher and Hill advocate use of a series parameterization - a general class of curves that contains the true $f_+(q^2)$ and is rich enough to describe all physical observables.

$$\boxed{f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,t_0)} \sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k}$$

Series Parameterization

$$\boxed{t_\pm \equiv \left(M_D \pm m_{\pi(K)}\right)^2, \quad z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}}$$

Hill & Becher, Phys. Lett. B 633, 61 (2006)

We fit our results with this parameterization!

We also fit with the older pole model, purely for the purposes of comparison with theory and other experiments.

Analysis Goals

We want to measure branching fractions for each of our four decay modes in ***multiple q^2 ranges***!

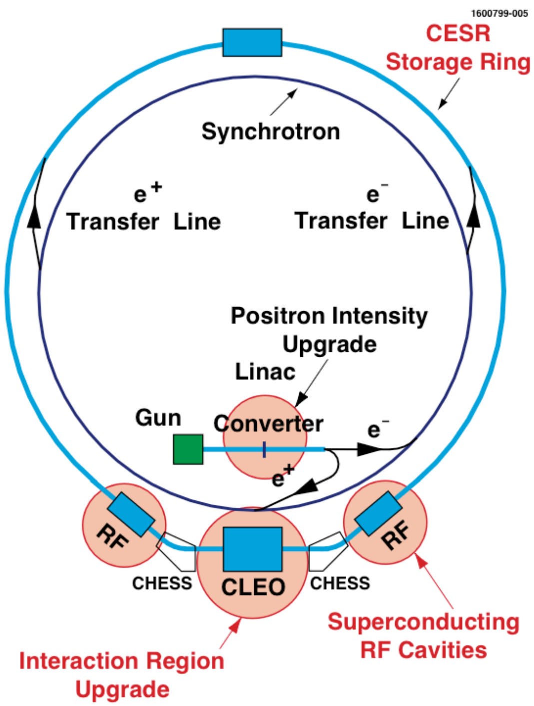
Allows us to measure $|V_{cs}|$ and $|V_{cd}|$ directly, using calculated form factors.

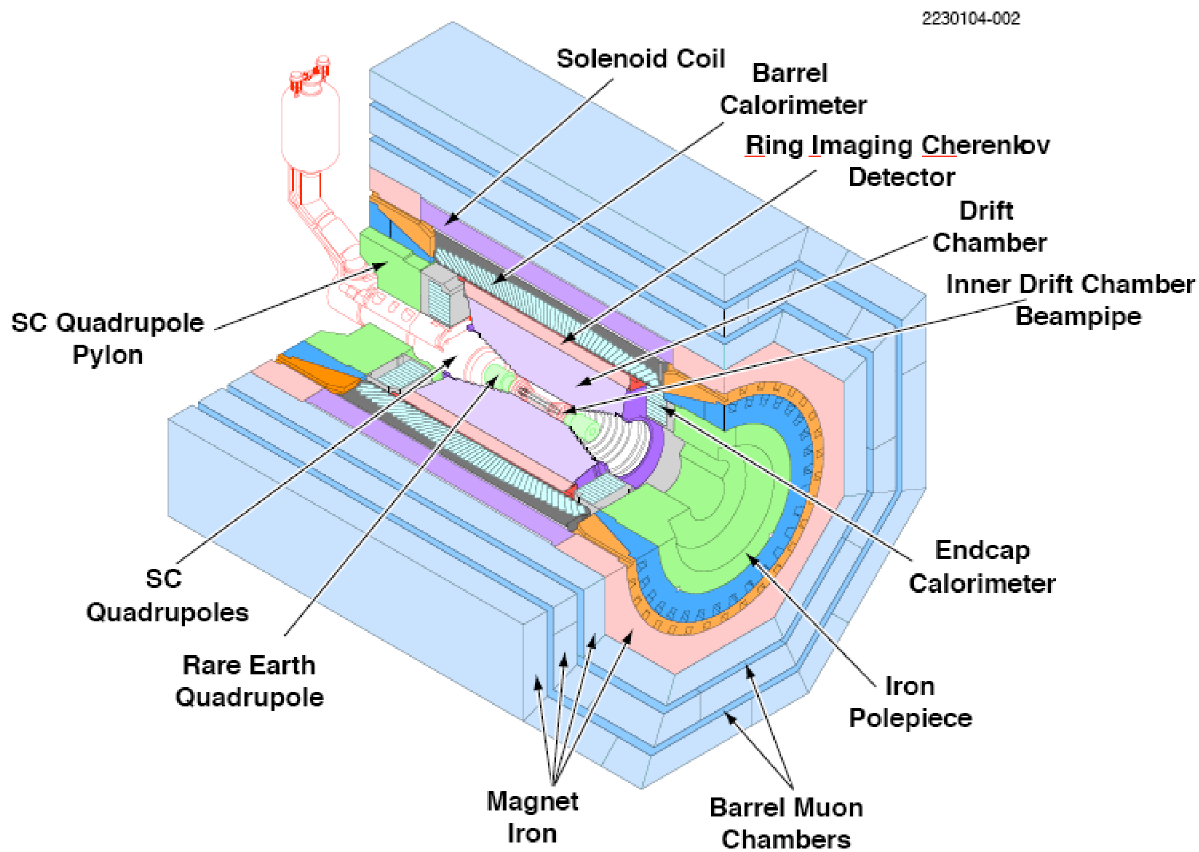
Allows us to make an accurate measurement of the $f_+(q^2)$ form factor for each mode.

We can test theoretical form factor predictions!

CLEO-c

*Relatively large **clean** data samples:*
This analysis 281/pb at ψ(3770).





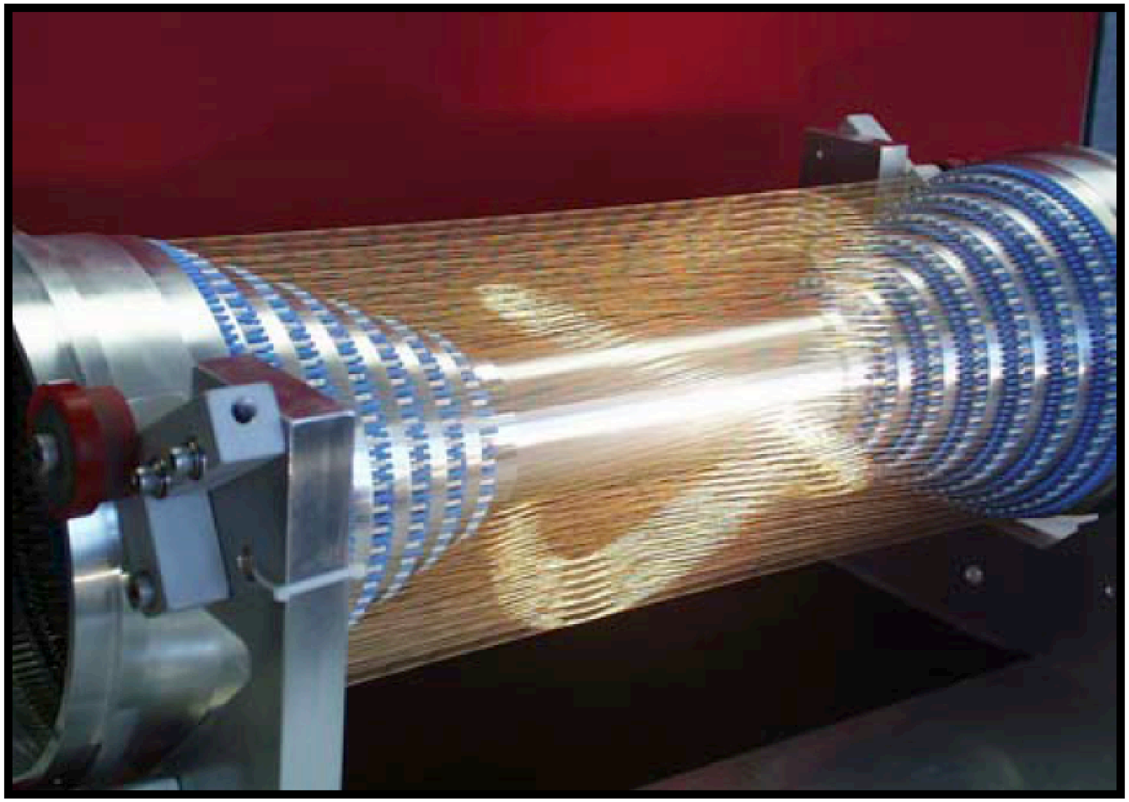
CLEO-c

Coverage: 93% of 4π

Track resolution: 0.6% at 1GeV

π^0 resolution: $\sigma \sim 6$ MeV

Excellent electron and PID: RICH & dE/dx

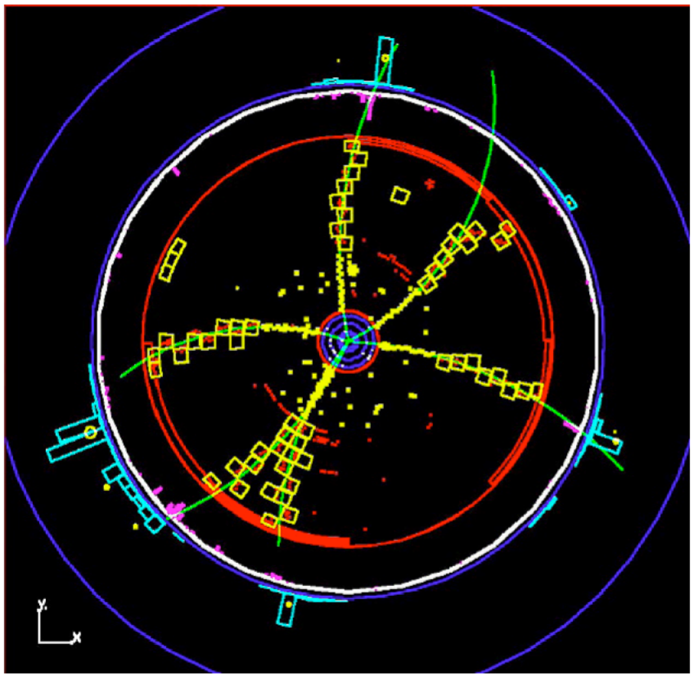


Inner Drift Chamber - ZD

CLEO-c - The ψ(3770) or ψ'' Charm Resonance

$\psi'' \rightarrow D\bar{D}$

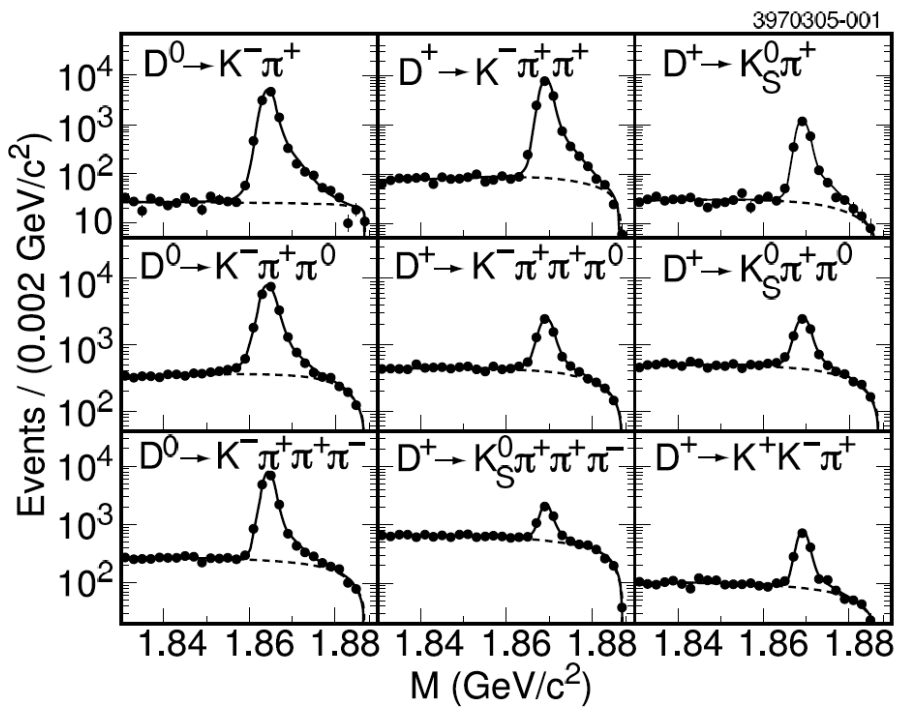
$D^+ \rightarrow K^- \pi^+ \pi^+$ $D^- \rightarrow K^+ \pi^- \pi^-$



$$N_{D\bar{D}} = \frac{N_i \bar{N}_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \bar{\varepsilon}_i}$$

"Single" tags *"Double" tags*

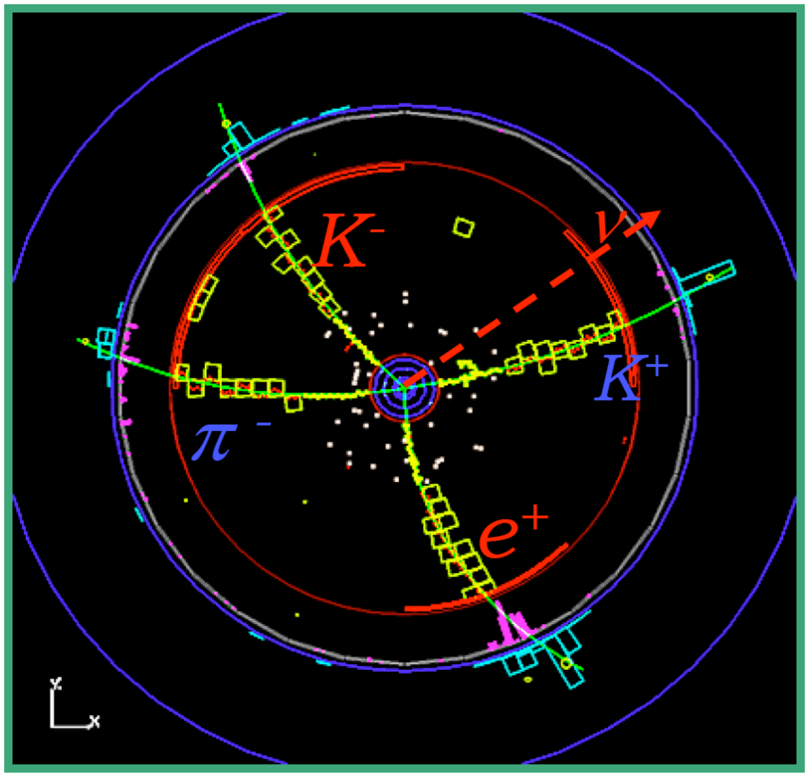
Many CLEO-c analyses use D tags. Hadronic branching fraction analysis, measures BF's and number of D pairs - cross sections!

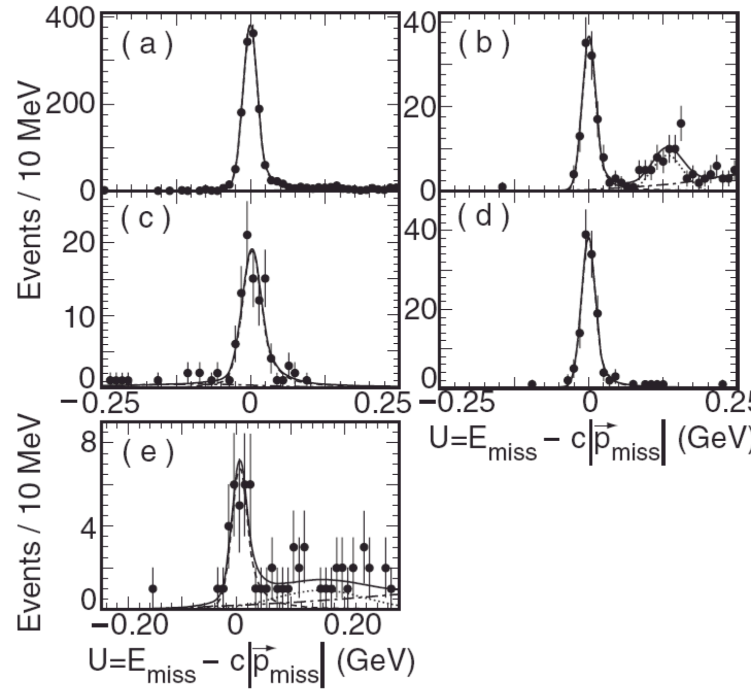


56/pb Analysis: PRL 95, 121801 (2005)

CLEO-c - First Semileptonic Results 56/pb

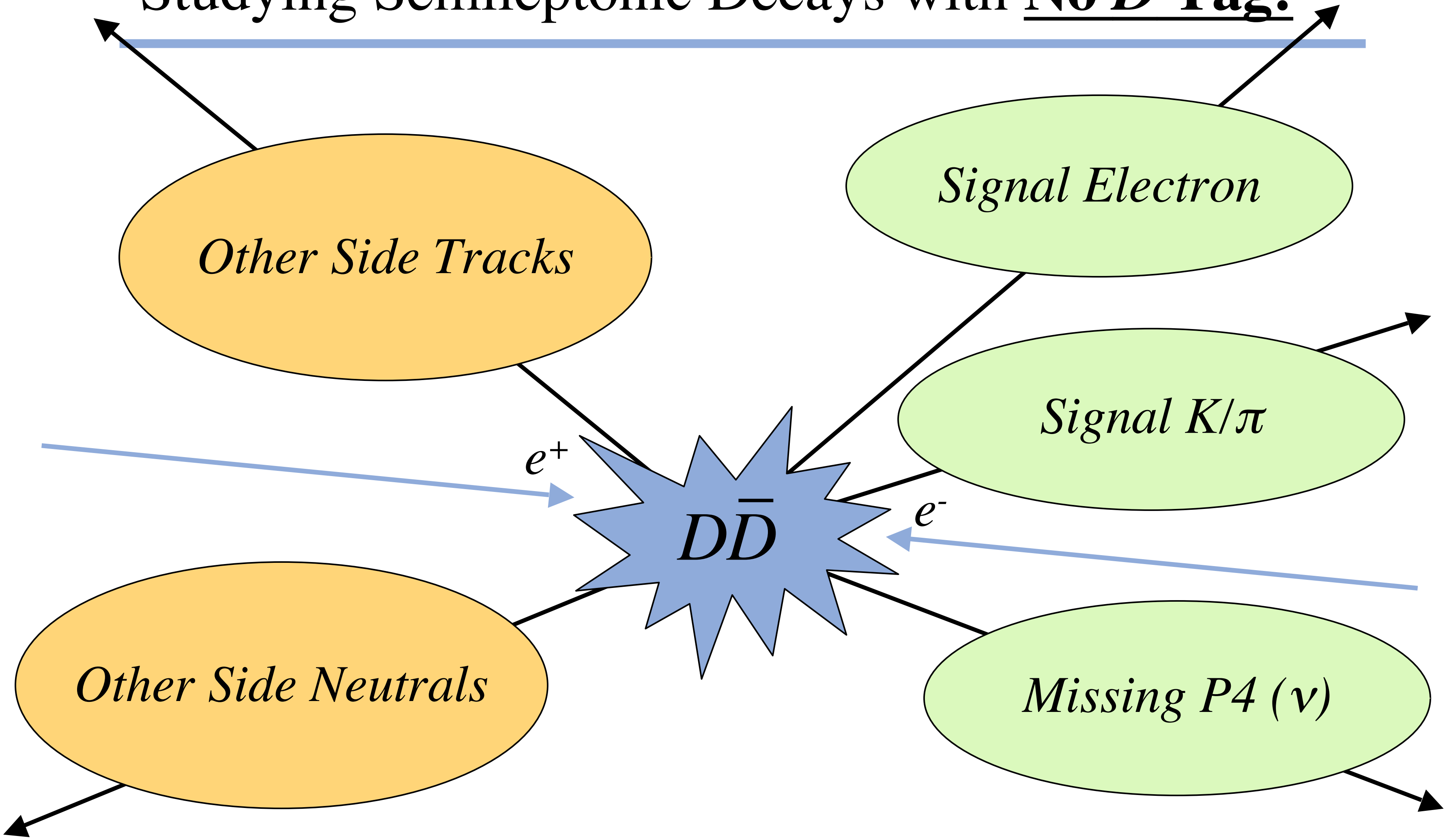
Tagged analyses *- look for D tag on one side of the event. Reconstruct a semileptonic (or leptonic) on the other.*
PRL 95, 181801 & 181802 (2005)
(PRL 95, 251801 (2005))





Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) (PDG)
$D^0 \to K^- e^+ \nu_e$	$3.44 \pm 0.10 \pm 0.10$	3.58 ± 0.18
$D^0 \to \pi^- e^+ \nu_e$	$0.26 \pm 0.03 \pm 0.01$	0.36 ± 0.06
$D^0 \to K^{*-}(K^- \pi^0) e^+ \nu_e$	$2.11 \pm 0.23 \pm 0.10$	2.15 ± 0.35
$D^0 \to K^{*-}(\bar{K}^0 \pi^-) e^+ \nu_e$	$2.19 \pm 0.20 \pm 0.11$	2.15 ± 0.35
$D^0 \to \rho^- e^+ \nu_e$	$0.19 \pm 0.04 \pm 0.01$	—
$D^+ \to \bar{K}^0 e^+ \nu_e$	$8.71 \pm 0.38 \pm 0.37$	6.7 ± 0.9
$D^+ \to \pi^0 e^+ \nu_e$	$0.44 \pm 0.06 \pm 0.03$	0.31 ± 0.15
$D^+ \to \bar{K}^{*0} e^+ \nu_e$	$5.56 \pm 0.27 \pm 0.23$	5.5 ± 0.7
$D^+ \to \rho^0 e^+ \nu_e$	$0.21 \pm 0.04 \pm 0.01$	0.25 ± 0.10
$D^+ \to \omega e^+ \nu_e$	$0.16^{+0.07}_{-0.06} \pm 0.01$	—

Studying Semileptonic Decays with **No *D* Tag!**



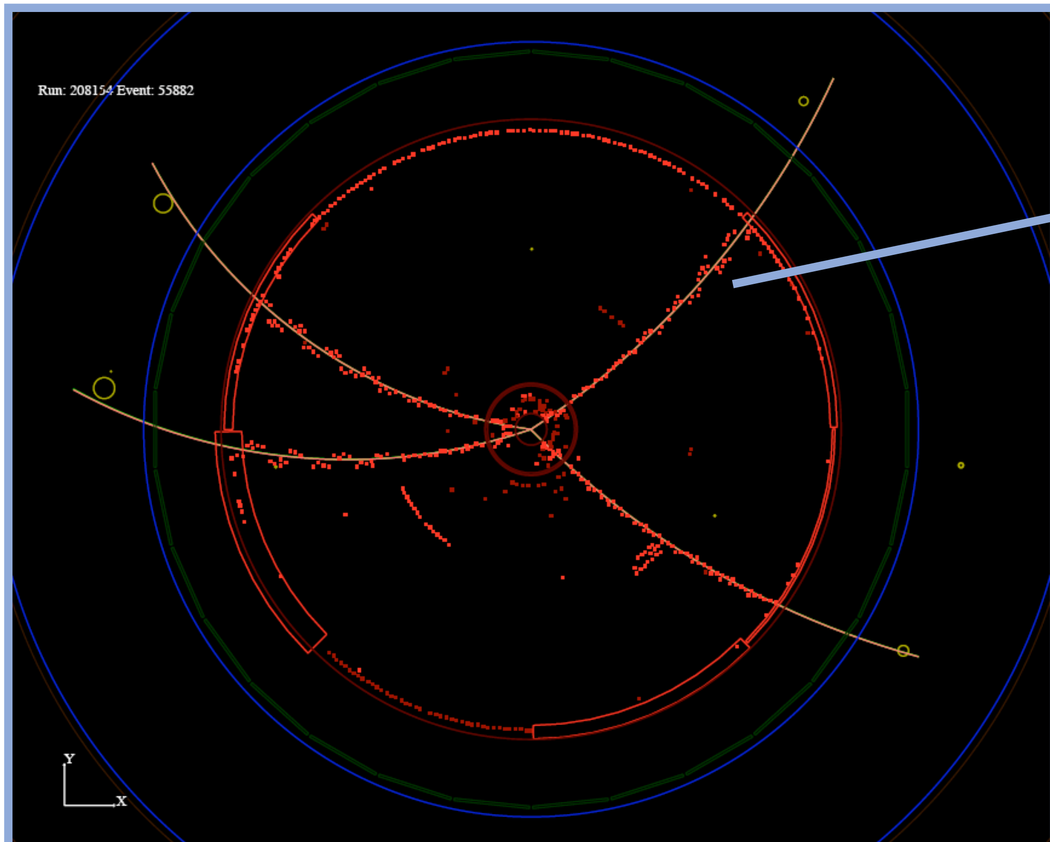
$$P_{event} = \left(2E_{beam}, \quad -2E_{beam}\sin\alpha, \quad 0, \quad 0\right)$$

$$P_{miss} = P_{event} - \sum P_{charged} - \sum P_{neutral}$$

ν Reconstruction - Cleaning Up The Event

Neutrino reconstruction is hard work!

To get the best possible resolution we assign the most likely PID to every track in the event using eId, RICH, dEdx & prod. fraction.

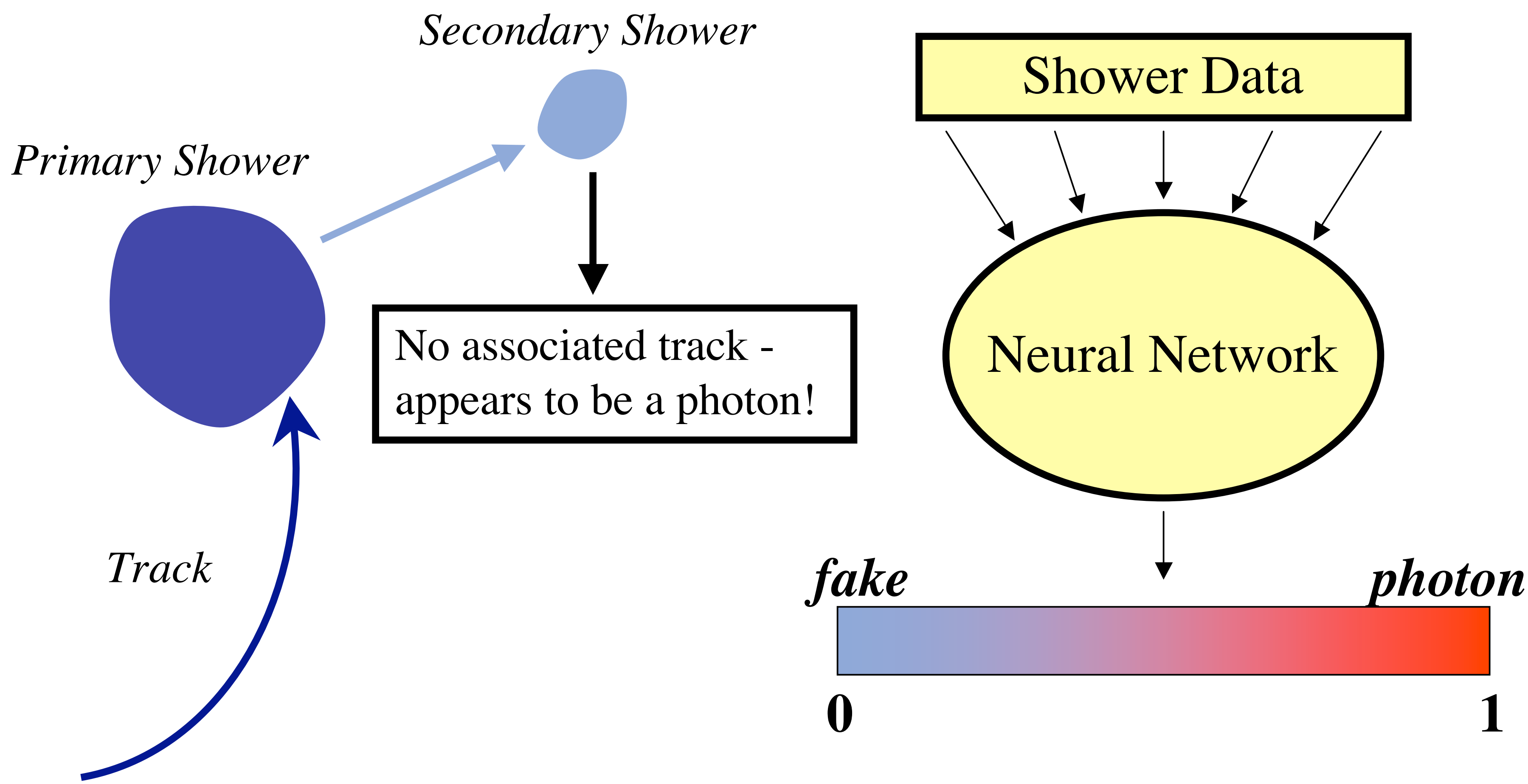


Is this track more likely to be an $e^{\pm}$, $\pi^{\pm}$ or $K^{\pm}$?

$$\sum p_{\text{charged}}$$

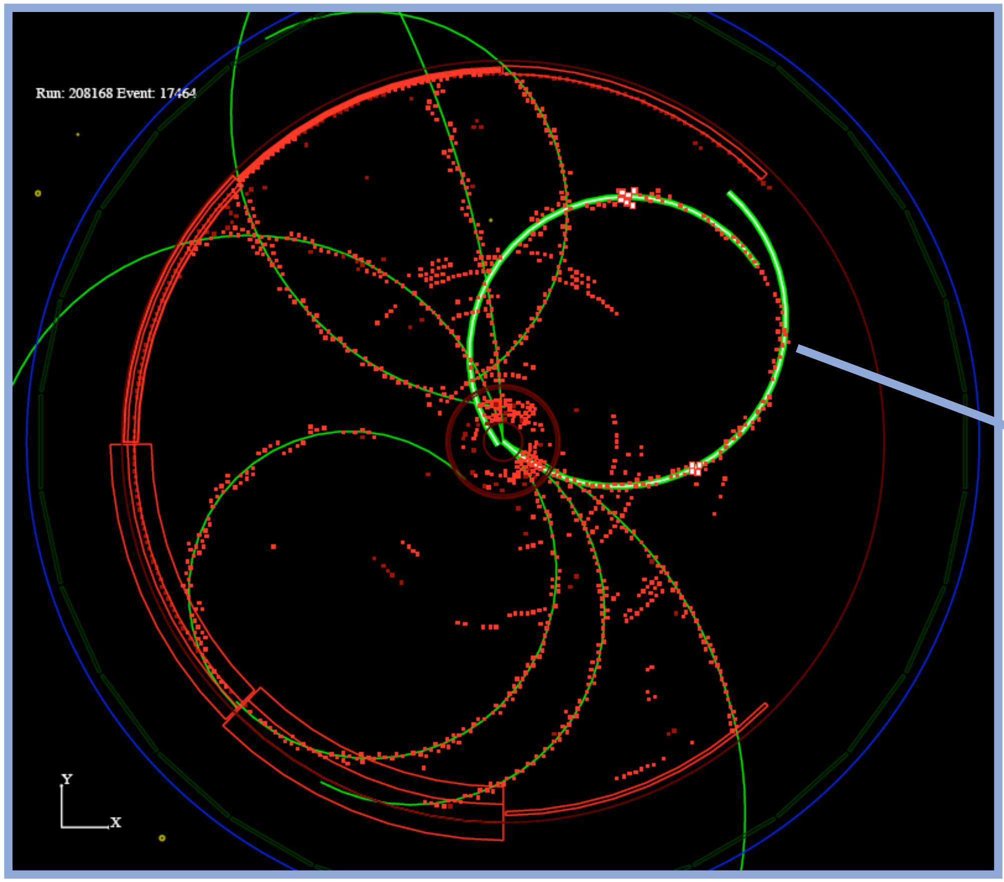
ν Reconstruction - Cleaning Up The Event

We have to remove as many spurious showers as possible from the **neutral energy sum**!



ν Reconstruction - Cleaning Up The Event

We have to make sure the **charged energy sums** contain only the tracks that we really want - no double counting!



- The highlighted track is a "curler".
- This particle's four momentum could easily be added twice!
- We have to remove the "back half" of the "curler".

ν Reconstruction - Resolution Cuts

To improve neutrino resolution we require:

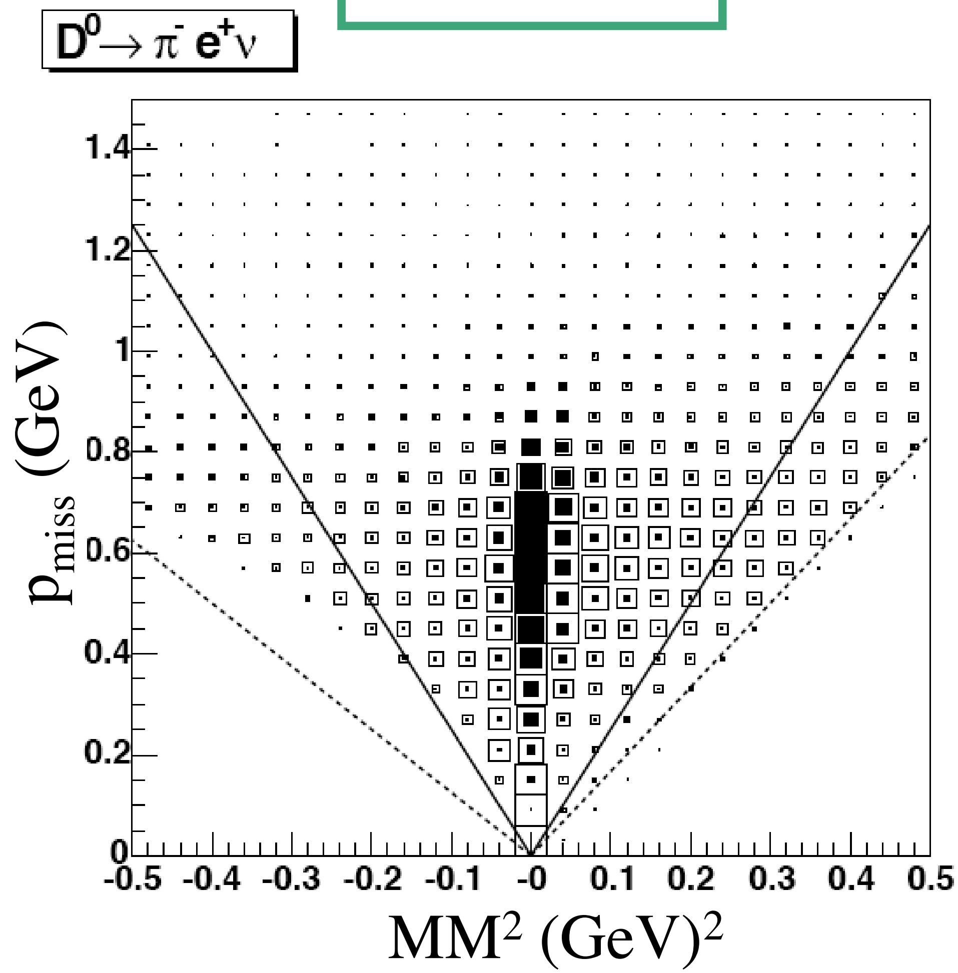
Event contains only one electron.

Total charge of the event is zero - $\Sigma Q = 0$.

Missing mass is consistent with zero - "Vee Cut"

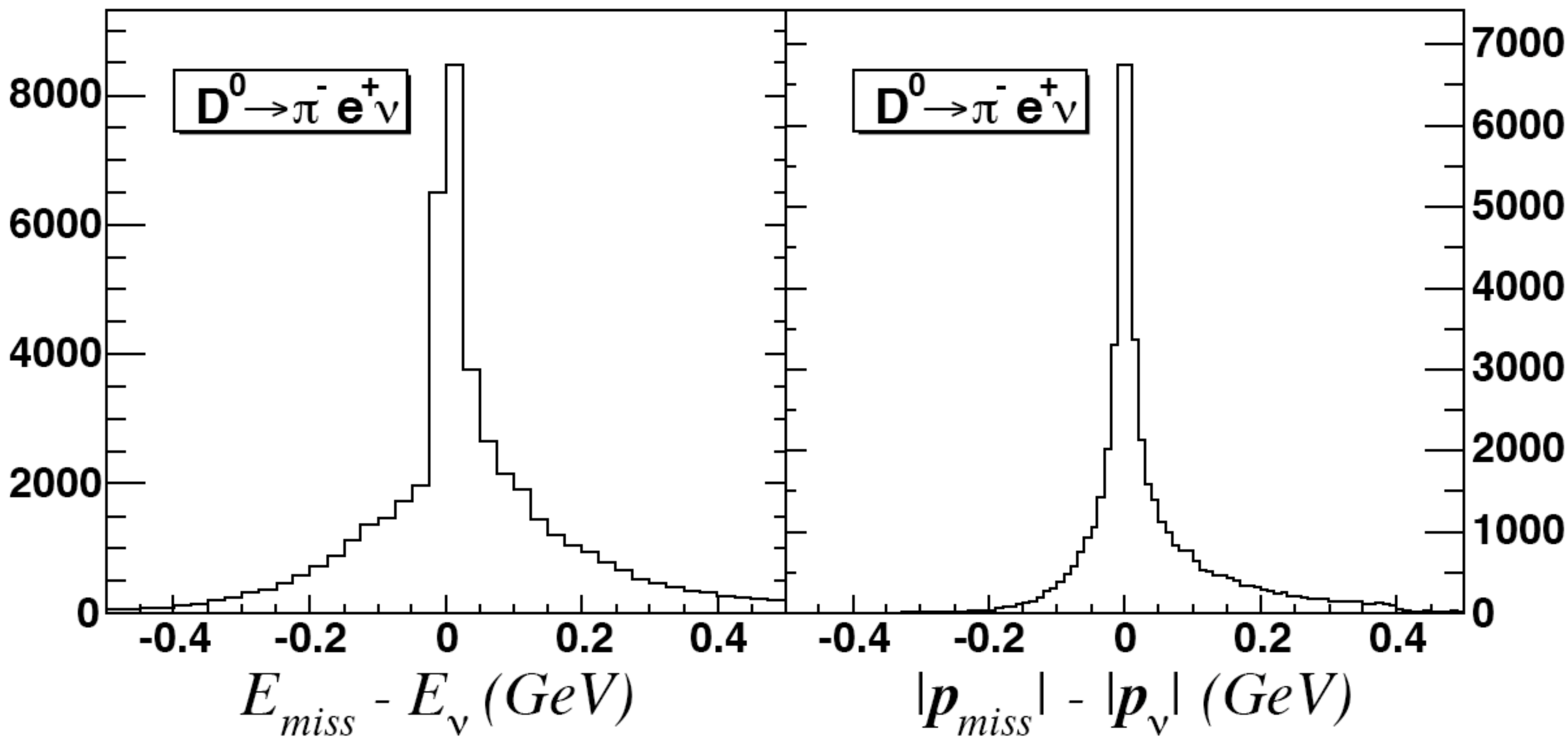
$$|MM^2/2p_{miss}| < 0.2$$

"Vee" Cut



Neutrino Resolution

σ ~ 0.02 GeV **σ ~ 0.01 GeV**



- Neutrino momentum resolution is ~2 times better than energy (spurious CsI showers and mass assignment).

D Candidates - Full Reconstruction

$$\boxed{\Delta E = E_{K(\pi)} + E_e + \left|\mathbf{p}_{miss}\right| - E_{beam}}$$

$$\boxed{M_{bc} = \sqrt{E_{beam}^2 - (\mathbf{p}_{K(\pi)} + \mathbf{p}_e + \beta \mathbf{p}_{miss})^2}}$$

β is a correction to the missing momentum

$$\boxed{E_{K(\pi)} + E_e + \beta\left|\mathbf{p}_{miss}\right| - E_{beam} \equiv 0}$$

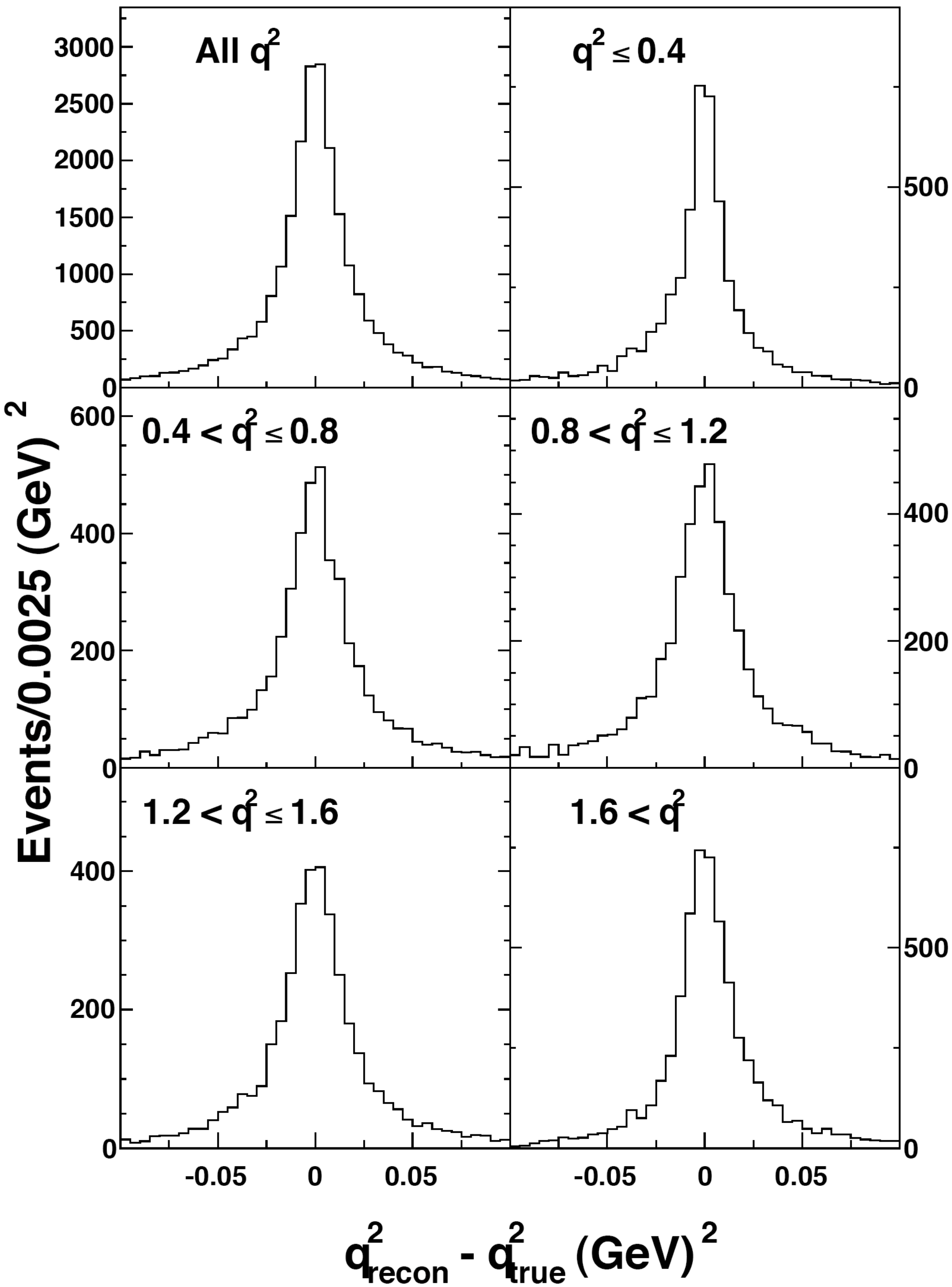
Event Selection

- <u>*D* Candidate Quality</u>
  - $-0.06 < |\Delta E| < 0.10$ GeV
  - More than one decay of same *D* charge choose best ΔE
  - Pion signal modes q^2 dependent other side ΔE cut
  - In π^0 signal mode remove events where $K^- e^+ \nu$ was also found & choose best ΔE in the event.
- <u>Remove Background Not In MC</u>
  - Event classification
  - Cut on $q_e cos\theta_e$ vs $q_e cos\theta_{miss}$ to remove possible 2γ background

$$\left.\right\}$$

Cuts tuned on independent MC samples to maximize:

$$\boxed{\frac{S^2}{S+B}}$$



q^2 Resolution

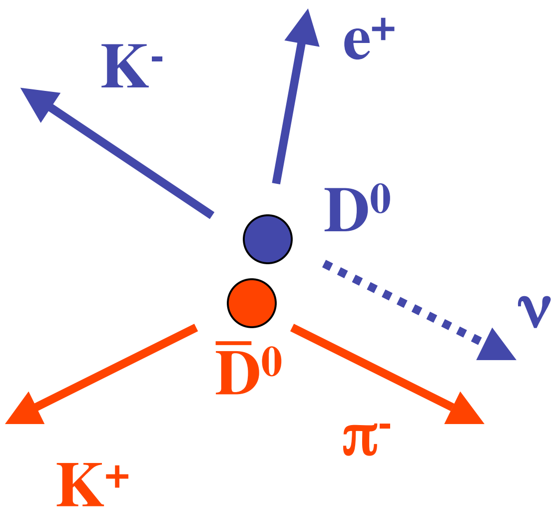
- Our q^2 resolution is about 0.03 $(\text{GeV})^2$, about 10× better than CLEO's $B\bar{B}$ sample at the $\Upsilon(4S)$!
- The resolution is roughly uniform over q^2 bins
- All four modes have about the same q^2 resolution, $D^+ \rightarrow \pi^0 e^+ \nu$ is slightly worse.

q^2 Resolution for $D^0 \rightarrow \pi^- e^+ \nu$ from signal monte carlo.

Backgrounds For This Analysis

Because we are doing ν reconstruction our backgrounds will be significant - especially for the Cabbibo suppressed pion modes.
We have to take care to get them right ... but first what are they?

Signal Mode Cross Feed



E.g. Swap in π^- from other side - reconstruct as $\pi^- e^+ \nu$

Generic $D\bar{D}$

MC generated using EvtGen and updated branching fractions from initial CLEO-c measurements.

Continuum

$$e^+e^- \to q\bar{q}$$

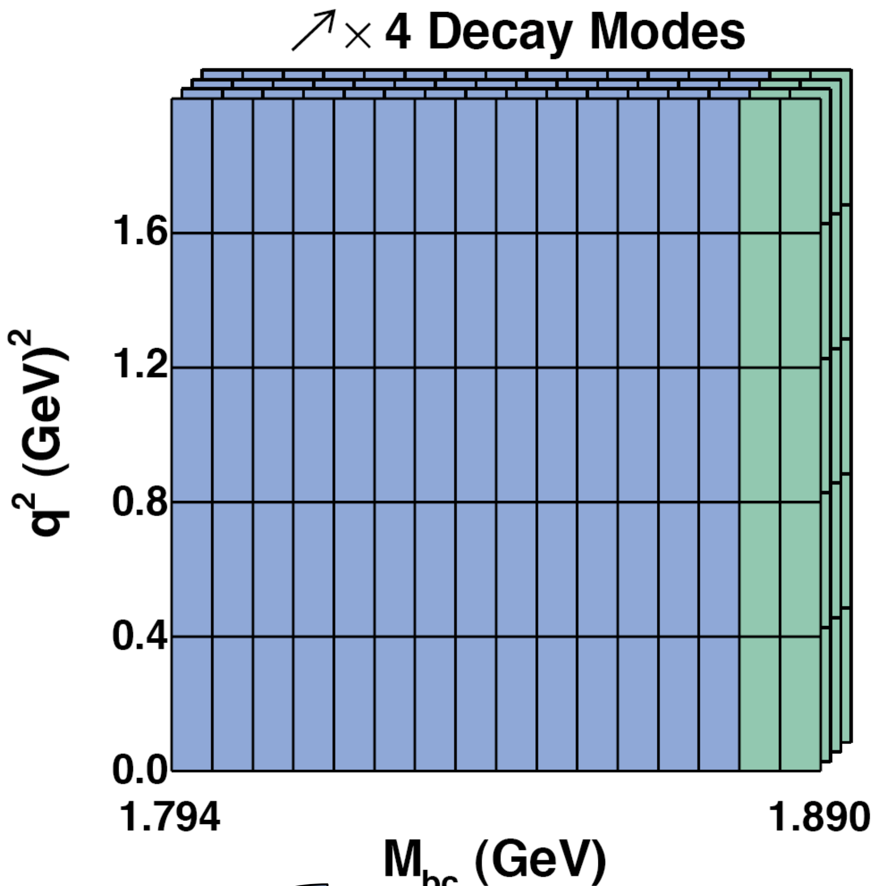
$$e^+e^- \to \tau^+\tau^-$$

$$e^+e^- \to \psi'\gamma$$

Fake Electrons

Events where the electron is faked by a hadron (π or K). In MC use only true electrons. Events with fake electrons are taken from data.

Fitting & The Fitter



- **We fit M_{bc} distributions of the four signal decay modes simultaneously.**
- We bin in both q^2 and M_{bc}, efficiency corrected yields are returned for each q^2 bin.
- For each bin and each decay mode we fit a number of input components to the data.
- The inputs come from MC *and* data.

$4 \times 5 = 20$ yield $+ 4\ D\bar{D} + 3\ M_{bc}$ resolution
$= 27$ free parameters

Fitting & The Fitter

Fit Components

Signal MC (*Binned in true q^2*)	Generic $D\bar{D}$ MC	Continuum MC	Fakes
$D^0 \to \pi^- e^+ \nu$ $D^0 \to K^- e^+ \nu$ $D^+ \to \pi^0 e^+ \nu$ $D^+ \to K_S(\pi^+\pi^-) e^+ \nu$ $D^+ \to K_S(\pi^0\pi^0) e^+ \nu$ $D^+ \to K_L e^+ \nu$	Fixed over q^2, but floating for each mode.	Fixed by cross section at ψ''.	In MC we use only **true** electrons. **Fakes** are from data, scaled by luminosity.

$\left.\begin{array}{l} D^+ \to K_S(\pi^0\pi^0) e^+ \nu \\ D^+ \to K_L e^+ \nu \end{array}\right\}$ *Fixed to $K_S \to \pi^+\pi^-$ signal mode.*

Fitting & The Fitter

We use a binned maximum likelihood fit, following the finite Monte Carlo statistics method of Barlow and Beeston (Comput. Phys. Commun. **77**, 219 (1993)).

$$\boxed{-2\ln L = -2\left(\sum_{i=1}^{n} d_i \ln f_i - f_i - d_i \ln d_i + d_i + \sum_{i=1}^{n}\sum_{j=1}^{m} a_{ji} \ln A_{ji} - A_{ji} - a_{ji} \ln a_{ji} + a_{ji}\right)}$$

Here d_i = data events in bin i, a_{ij} = MC source j events in bin i, the A_{ij} are the expected number of MC events for the a_{ji}. With each A_{ji} having strength p_j, the f_i are given by $f_i = \Sigma\, p_j A_{ji}$.

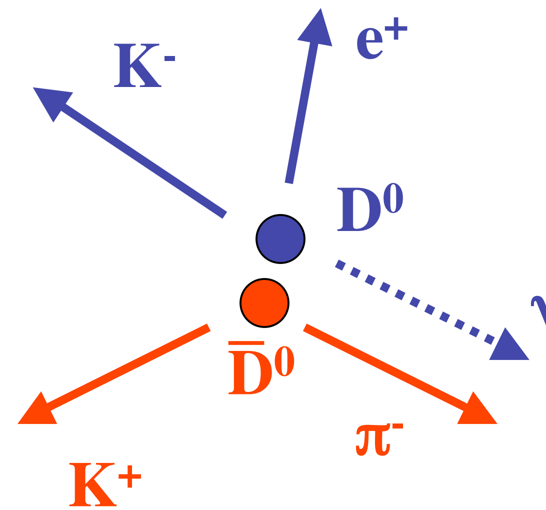
We have relatively large statistics $\Rightarrow$ can interpret -2lnL as a χ^2 (also adding necessary constant terms). We use this as a goodness of fit test!

MC Corrections

We need to make corrections to the generic MC for our nominal fit! This affects our background levels.

Cross Feed Corrections

$\pi^{\pm}$ Production in Generic MC
π^{0} Production in Generic MC
$K^{\pm}$ faking $\pi^{\pm}$



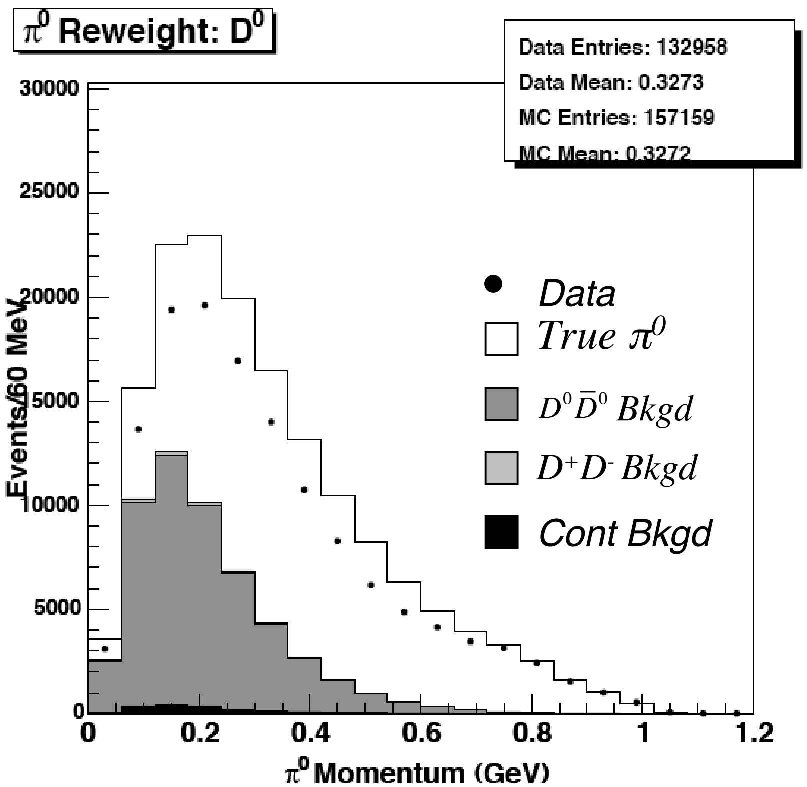
*E.g. Get background in signal $\pi^{-}e^{+}\nu$ events from **other side** of $K^{-}e^{+}\nu$ events. Need to get $\pi^{\pm}$ production right in generic MC!*

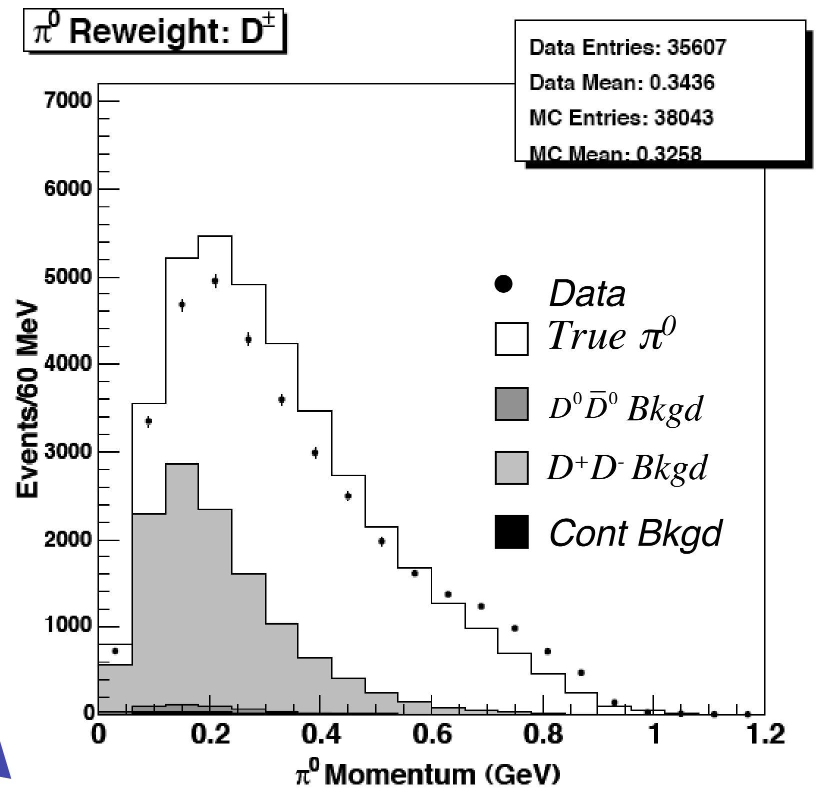
Efficiency Corrections

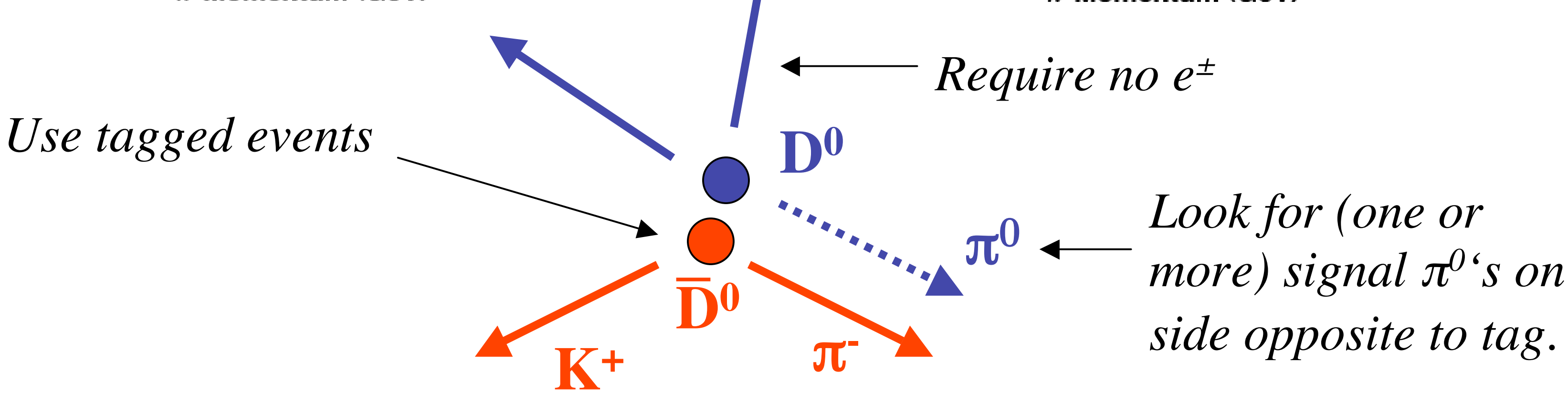
K_L Production
Fake/Spurious Tracks
Signal Particle PID/Finding Efficiency

Final State Radiation (FSR) Re-weight

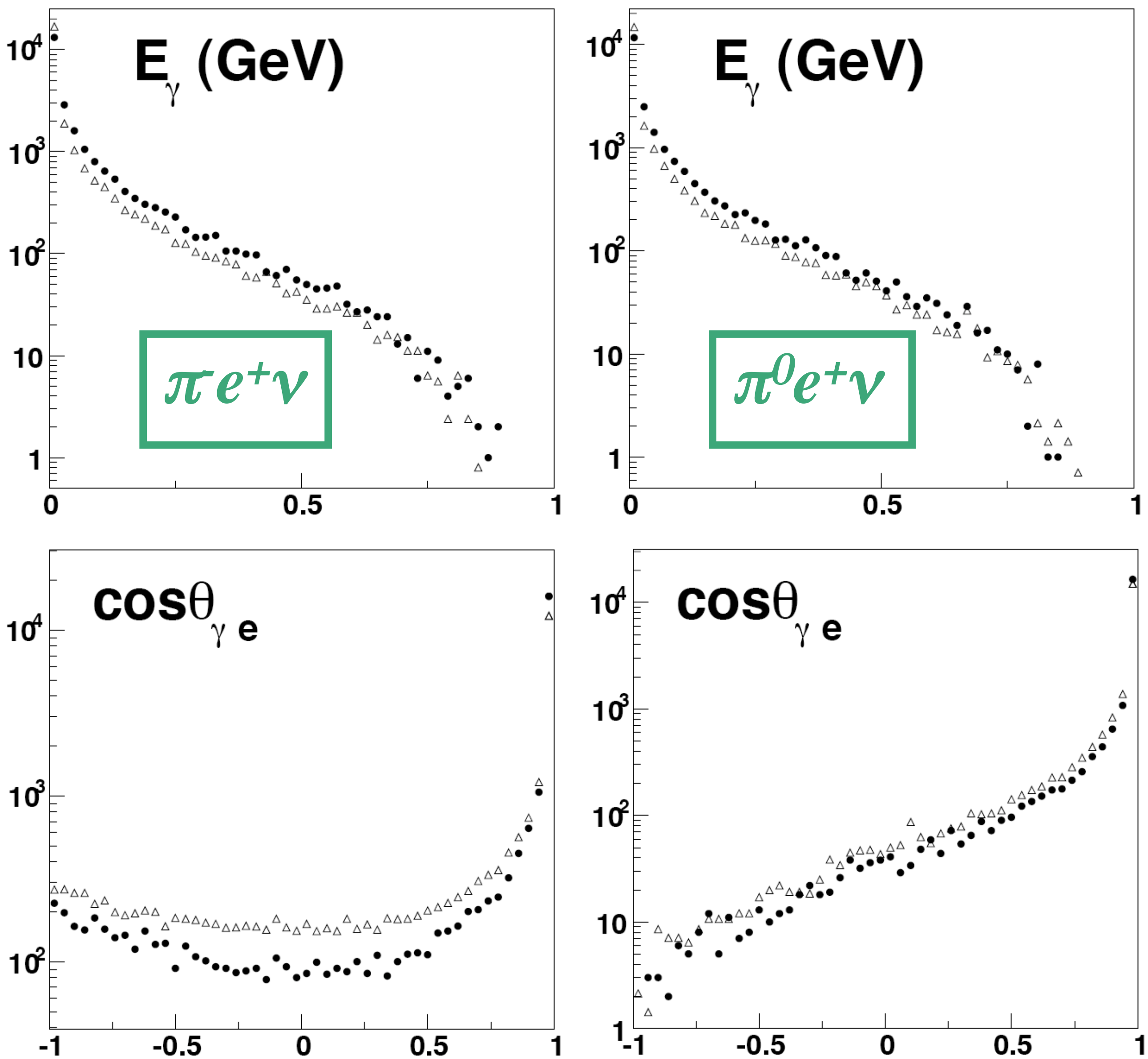
MC Corrections - Example π^0 Re-weight







MC Corrections - Example FSR Re-weight

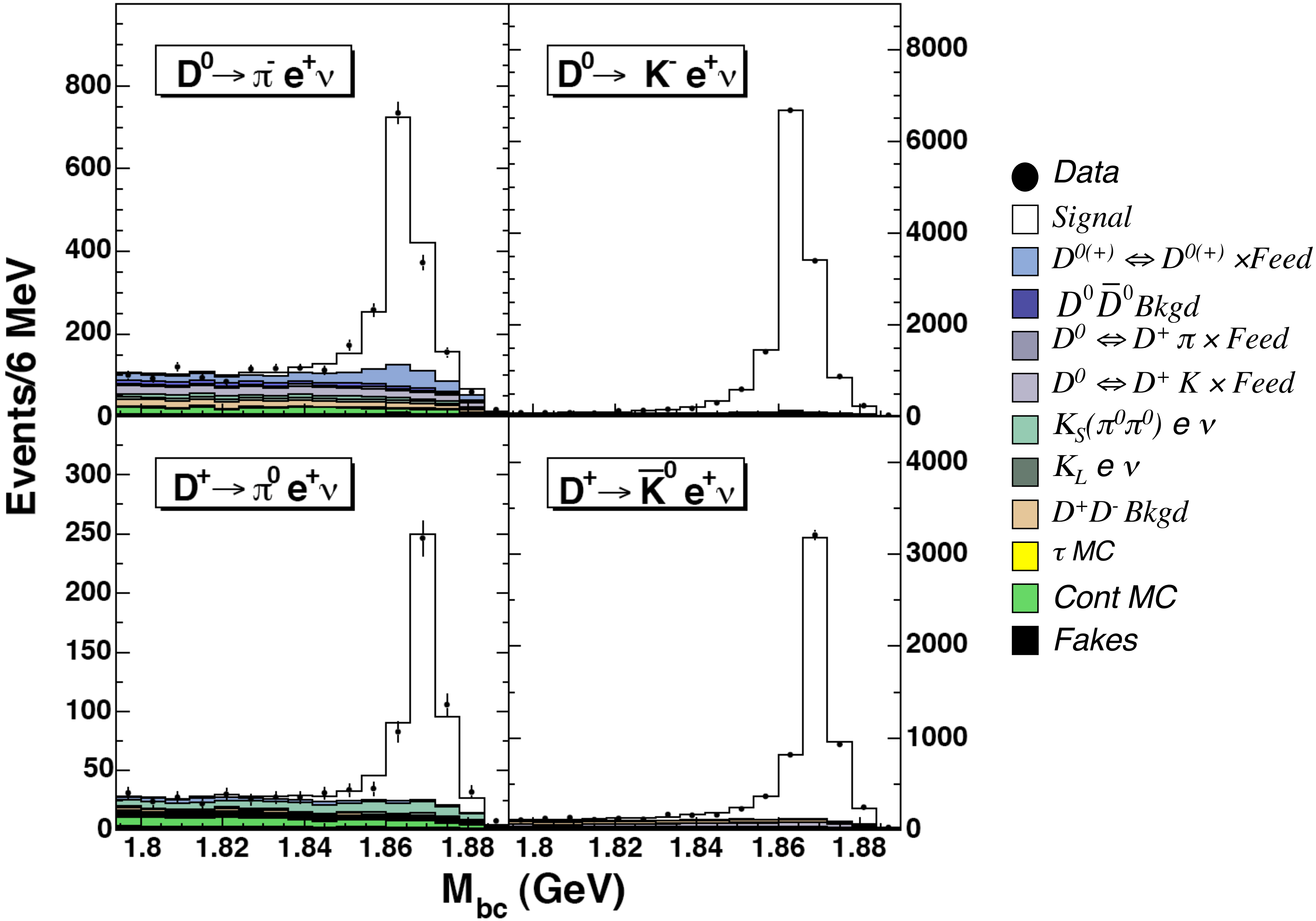


PHOTOS ●
KLOR △
(hep-ph/0406006)

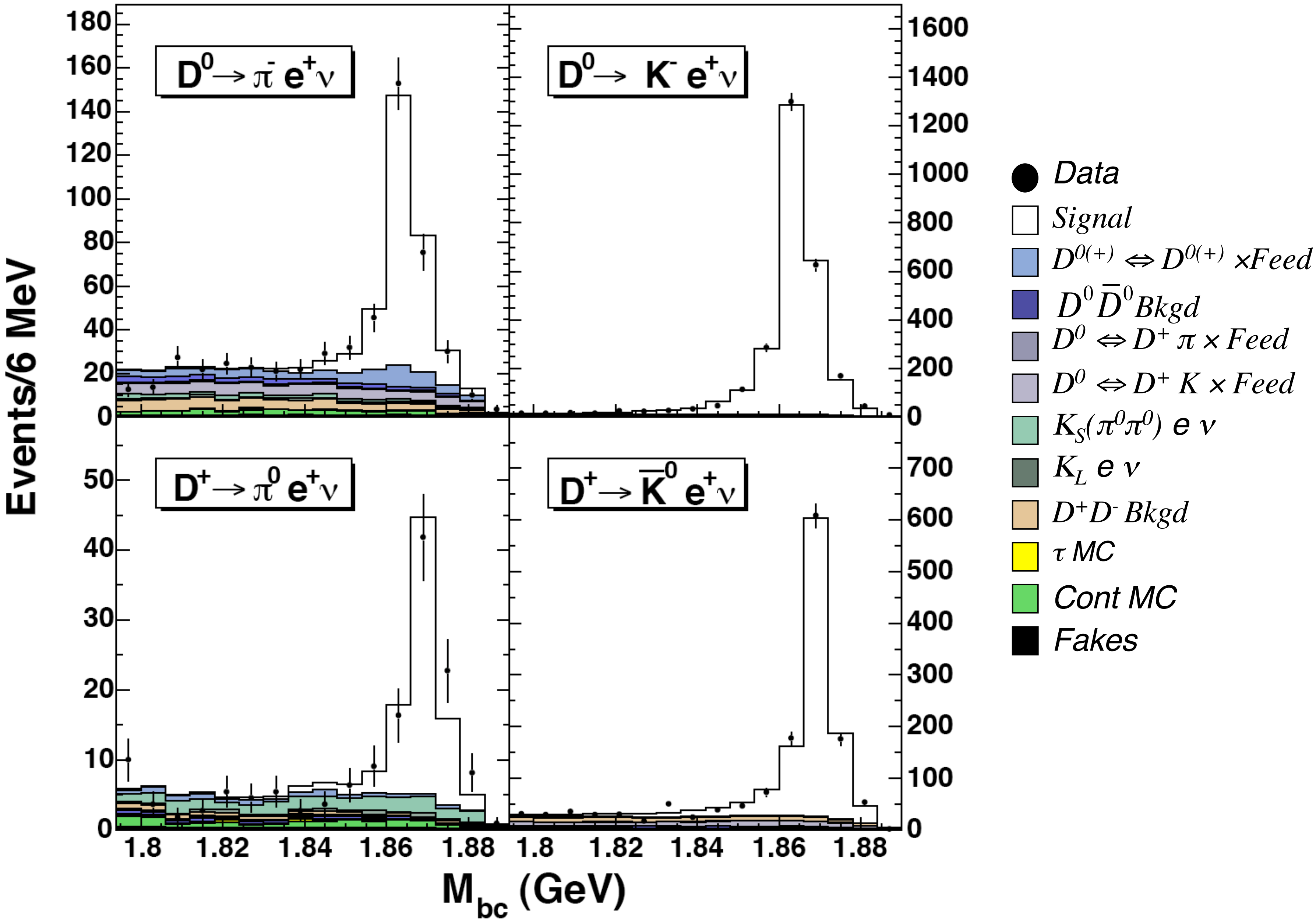
Original Signal MC generated with PHOTOS.

Use these spectra to perform a 2D re-weight to gain the corrected KLOR distributions.

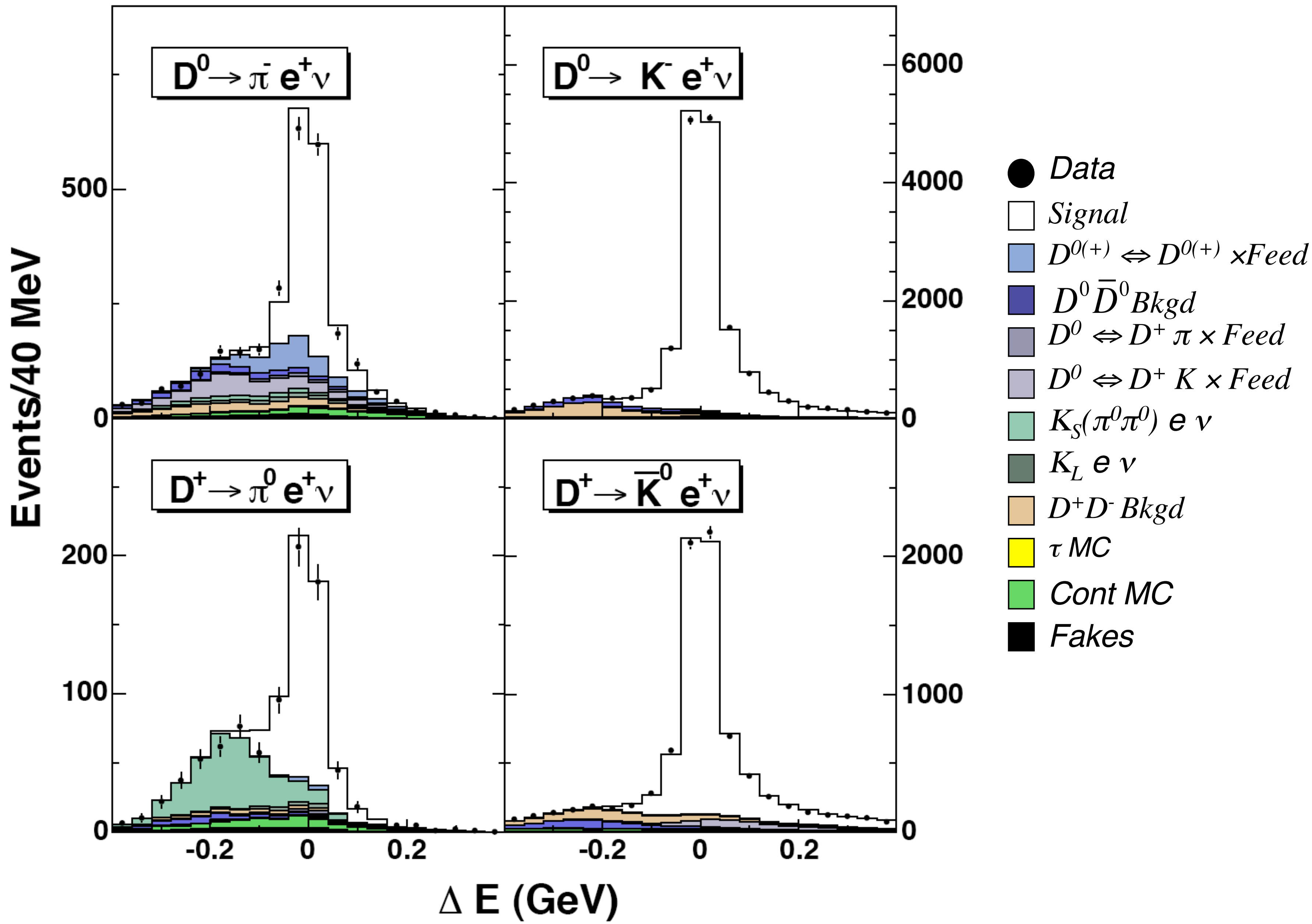
Fit Results - M_{bc} Plots Integrated Over q^2



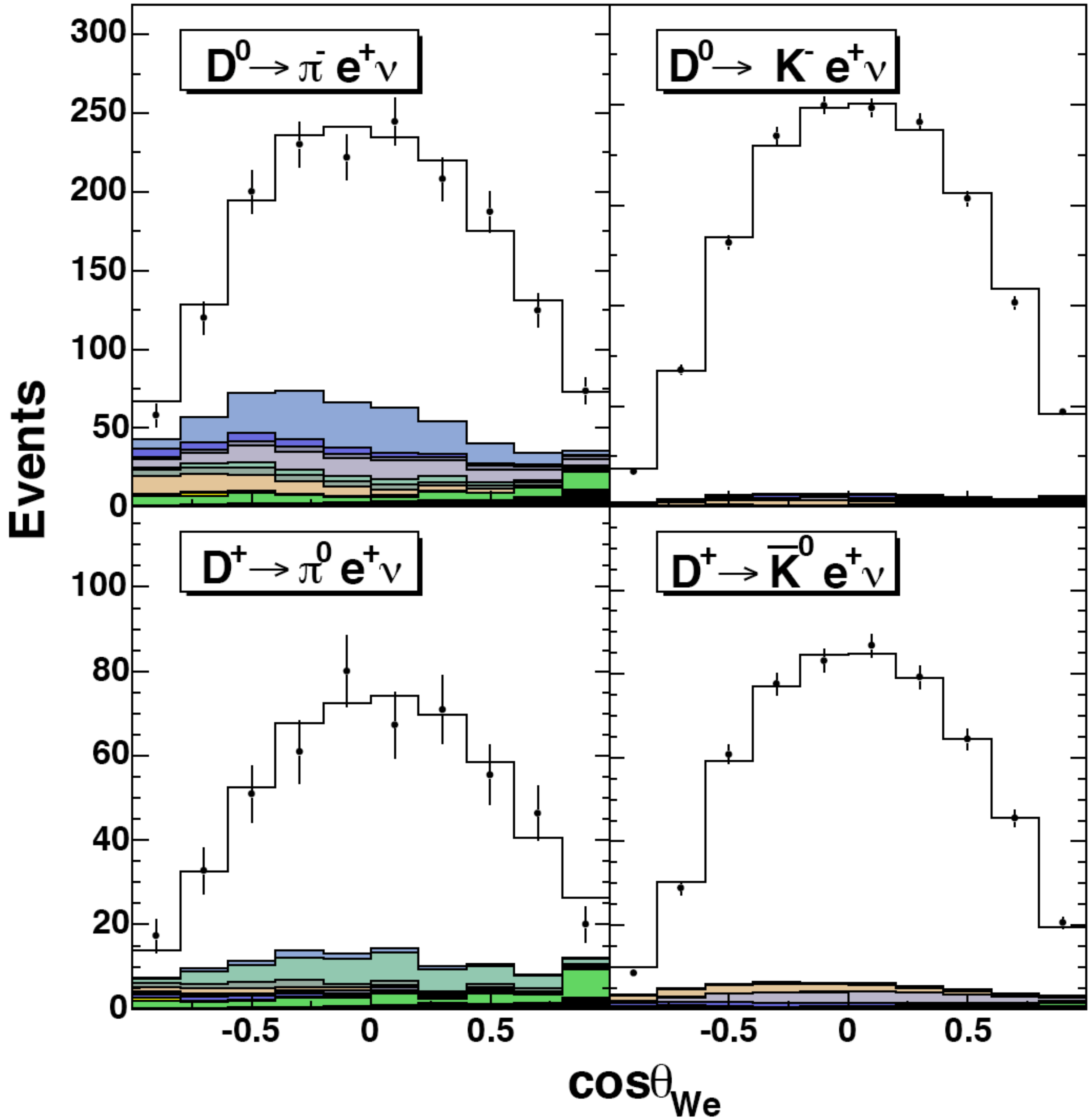
Fit Results - M_{bc} Plots: $0.8 < q^2 < 1.2$

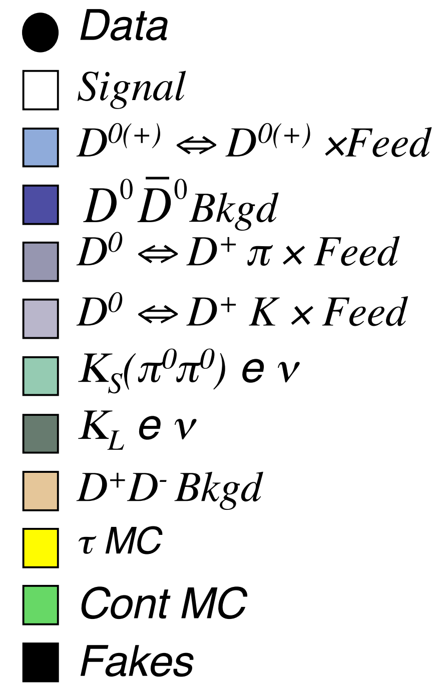


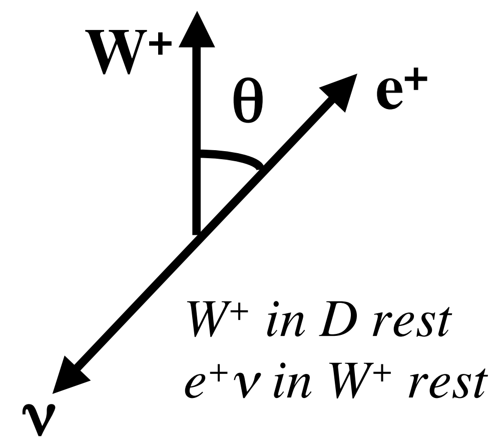
Fit Results - ΔE Plots ($|M_{bc}-M_D| < 0.015$ GeV)



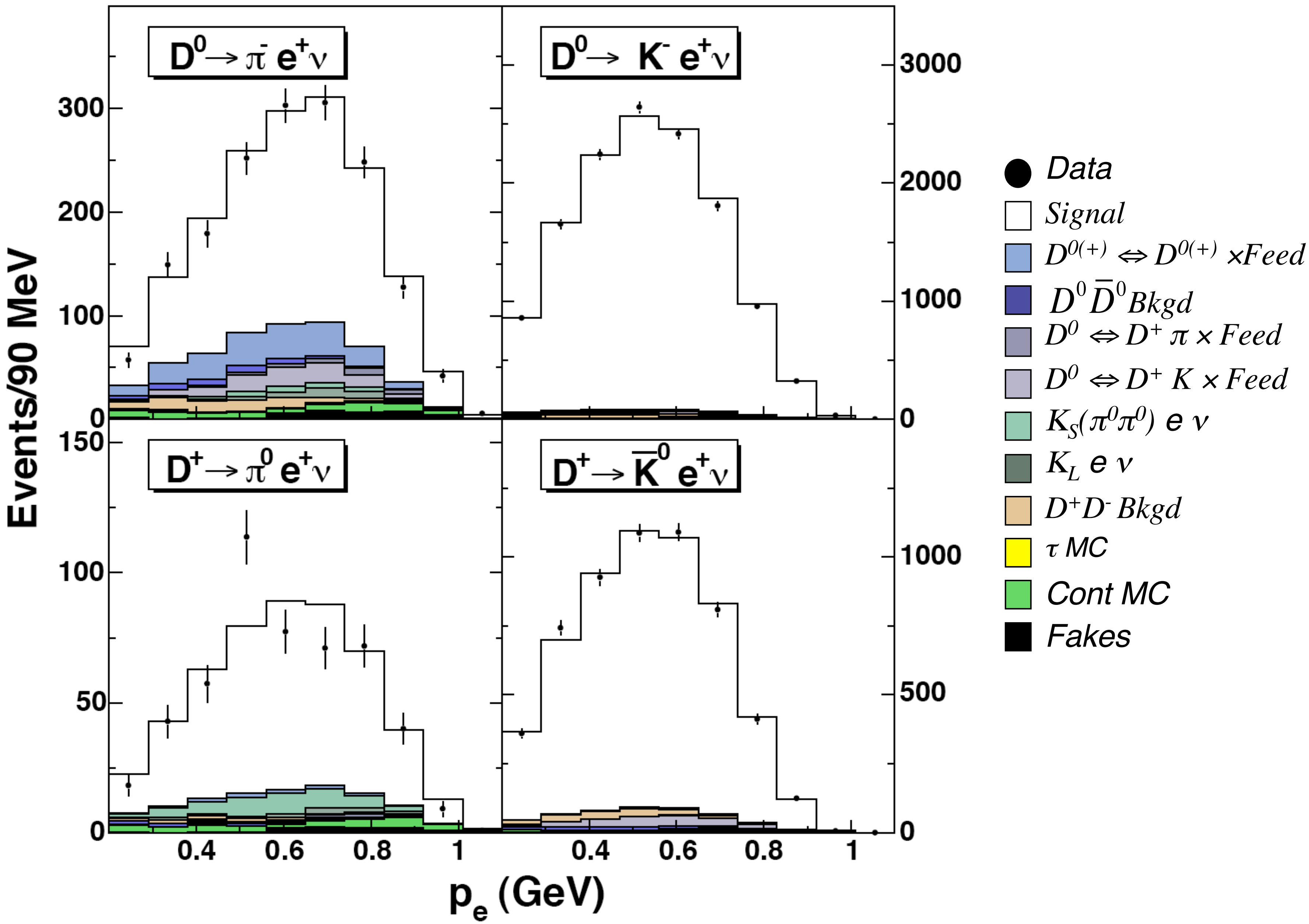
Fit Results - $\cos\theta_{We}$ Plots ($|M_{bc}-M_D| < 0.015$ GeV)







Fit Results - p_e Plots ($|M_{bc}-M_D| < 0.015$ GeV)



Raw Yields and Efficiencies By q^2 Bin

	q^2 Interval					
***D* Decay**	**0.0 - 0.4**	**0.4 - 0.8**	**0.8 - 1.2**	**1.2 - 1.6**	**≥ 1.6**	**All q^2**
$D^0 \rightarrow K^- e^+ \nu$	5734 ± 51	4433 ± 45	2807 ± 35	1281 ± 23	140 ± 8	14395 ± 78
	19.4%	20.8%	20.3%	18.5%	14.1%	19.8%
$D^0 \rightarrow \pi^- e^+ \nu$	289 ± 13	258 ± 12	279 ± 12	207 ± 11	313 ± 13	1346 ± 28
	19.8%	21.5%	22.9%	23.3%	22.8%	21.9%
$D^+ \rightarrow K_S e^+ \nu$	2282 ± 35	1767 ± 31	1125 ± 24	568 ± 17	101 ± 8	5841 ± 54
	11.8%	12.4%	12.7%	12.5%	12.8%	12.2%
$D^+ \rightarrow \pi^0 e^+ \nu$	107 ± 9	126 ± 9	77 ± 8	74 ± 7	64 ± 6	450 ± 17
	7.6%	8.1%	8.1%	7.3%	5.8%	7.4%

$$-2 ln L = 255.817 \text{ for } 280 - 27 = 253 \text{ } d.o.f$$

Systematic Error Summary (%)

Systematic	$\pi^- e^+ \nu$	$K^- e^+ \nu$	$\pi^0 e^+ \nu$	$\bar{K}^0 e^+ \nu$
ν simulation	1.69	1.80	1.96	1.74
signal hadron	0.41	0.30	0.53	1.00
signal e^+	0.60	0.67	0.53	0.51
π^0 production	0.03	0.00	0.04	0.01
π^- production	0.24	0.01	0.29	0.04
K^- faking π^-	0.58	0.00	0.05	0.01
π^- smear	0.95	0.01	0.05	0.01
K^- smear	0.03	0.09	0.00	0.01
π^0 smear	0.02	0.00	2.09	0.01
e^+ veto	0.00	0.05	0.07	0.04
FSR	1.28	0.66	0.98	0.88
Model dependence	0.19	0.02	0.28	0.06
Number $D\bar{D}$	2.29	2.29	2.70	2.70
Total	3.40	3.06	4.21	3.53

These will shrink to ~1% SOON!

ν Uncertainties & Systematics Example

Neutrino Simulation Uncertainties

Hadronic Showers, Shower Resolution, Shower Neural Net, Track Finding Efficiency, Track Resolution, Fake Tracks, Neutrino PID, K_L Showers, K_L Re-weight

Example: Track Finding Efficiency

Study CLEO-c $\psi(2S) \rightarrow J/\psi\pi\pi$ data to find tracking efficiencies in data and MC.

Take efficiency difference and its error summed in quadrature …

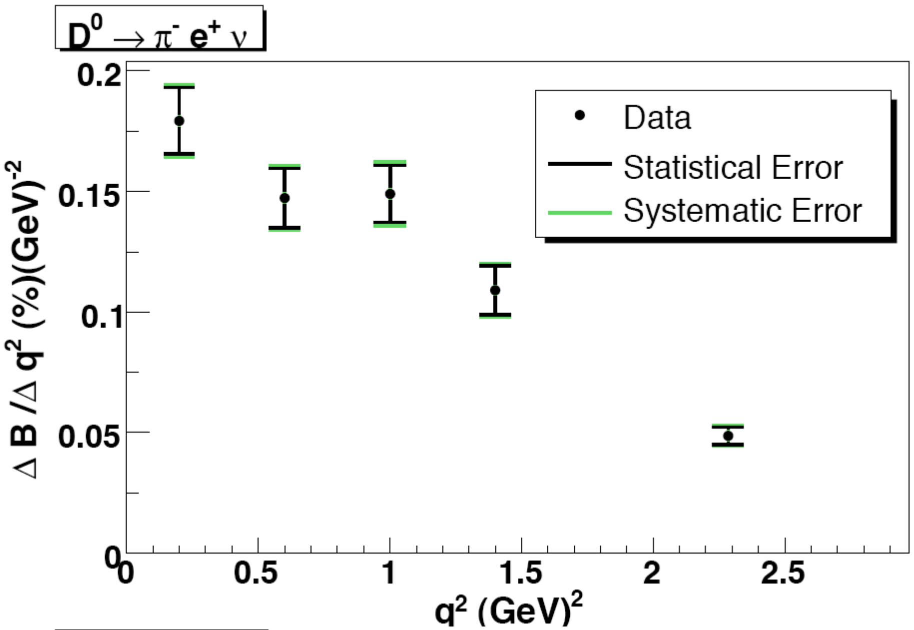
Run over MC throwing dice to drop this fraction of tracks from events.

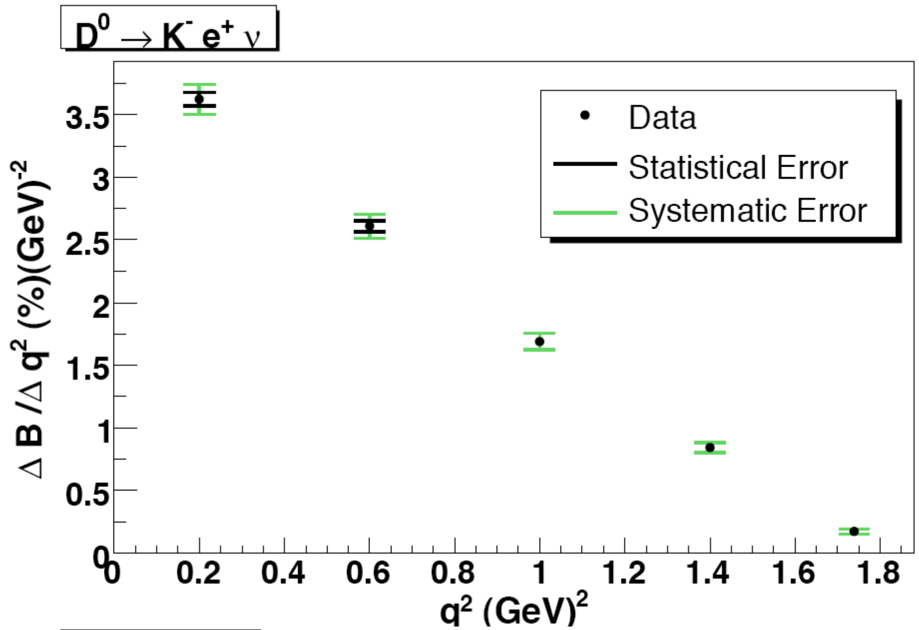
$D^0 \rightarrow \pi^- e^+ \nu$

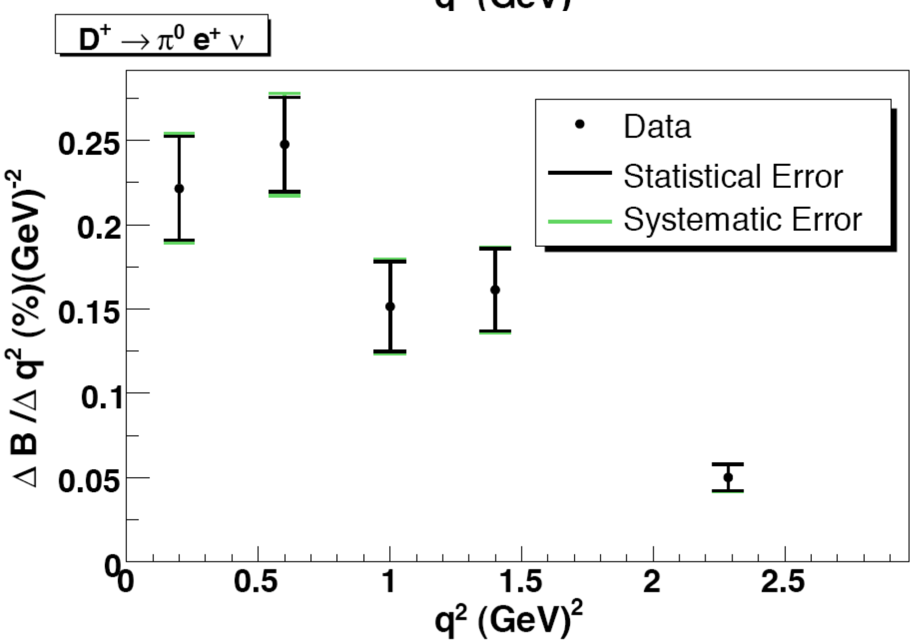
Nominal BF (%)	*Dropped Track BF (%)*	*Diff/Syst Error*
0.301	*0.303*	*0.002*

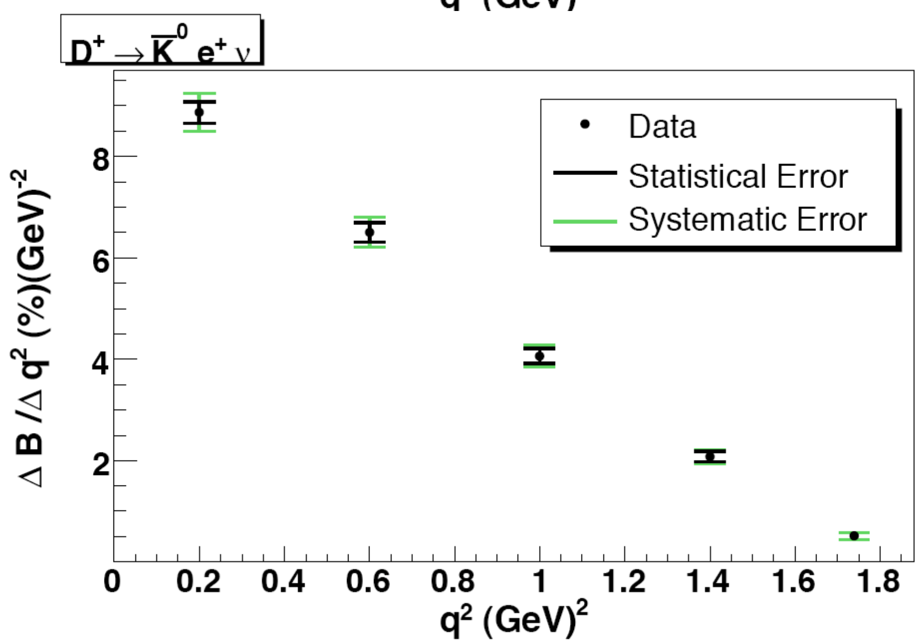
Re-fit MC to get new yields and branching fractions.

Branching Fraction Result Plots









Preliminary!

Branching Fractions: $B = Y/(2N_{D\bar{D}})$

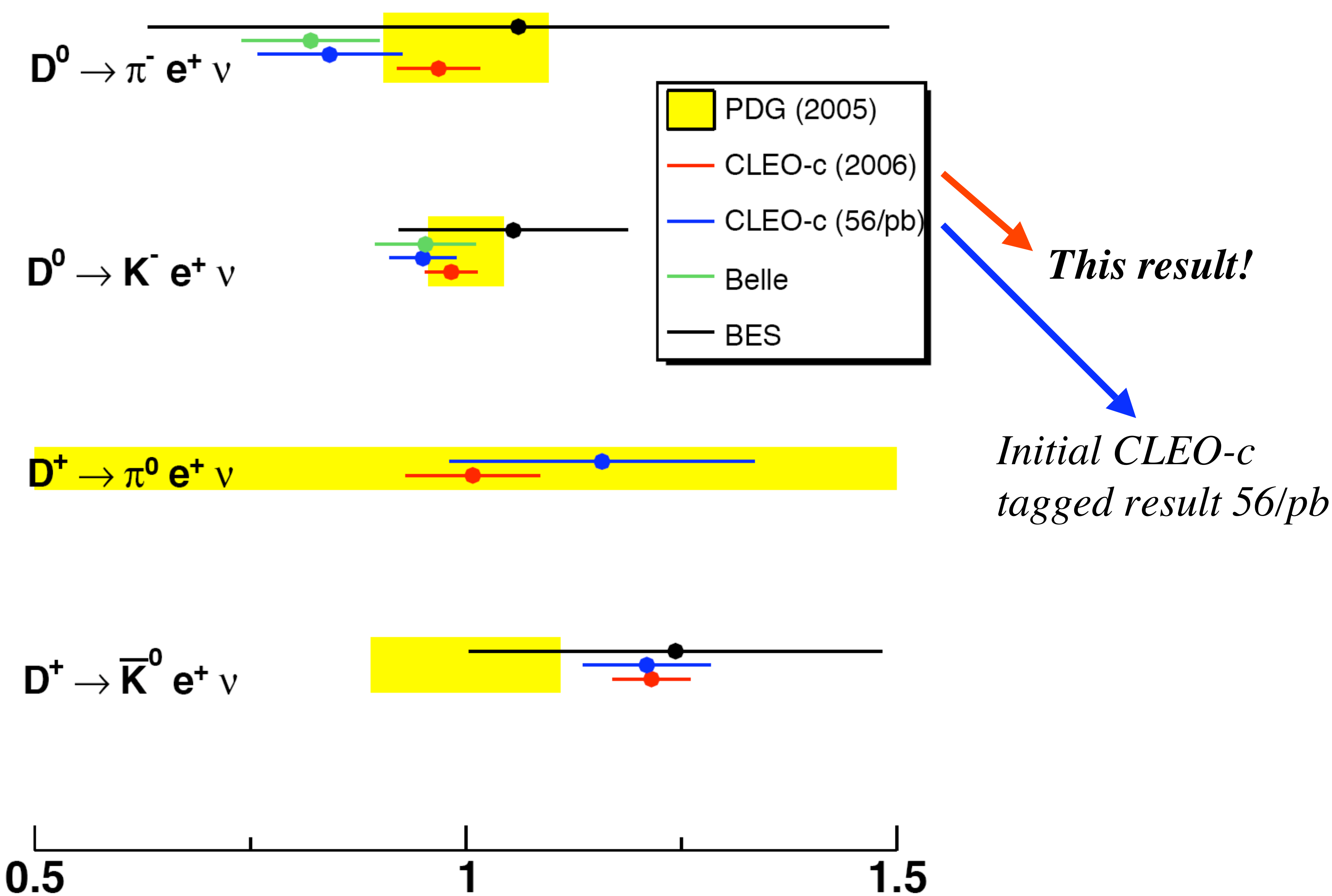
D Decay	Br. Frac. (%)	PDG Value (%)
$D^0 \to K^- e^+ \nu$	**3.56 ± 0.03 ± 0.11**	**3.62 ± 0.16**
$D^0 \to \pi^- e^+ \nu$	**0.301 ± 0.011 ± 0.010**	**0.311 ± 0.030**
$D^+ \to \bar{K}^0 e^+ \nu$	**8.75 ± 0.13 ± 0.30**	**7.2 ± 0.8**
$D^+ \to \pi^0 e^+ \nu$	**0.383 ± 0.025 ± 0.016**	**0.38 ± 0.19**

Integrated over q^2.

Ratio	Measured (%)	PDG (%)	Ratio	Measured
$\frac{D^0 \to \pi^- e^+ \nu}{D^0 \to K^- e^+ \nu}$	**8.5 ± 0.3 ± 0.1**	**8.6 ± 0.7**	$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D^+ \to \pi^0 e^+ \nu)}$	**1.99 ± 0.15 ± 0.10**
$\frac{D^+ \to \pi^0 e^+ \nu}{D^+ \to \bar{K}^0 e^+ \nu}$	**4.4 ± 0.3 ± 0.1**	**4.6 ± 1.4 ± 1.7**	$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu)}$	**1.03 ± 0.02 ± 0.04**

Preliminary!

Branching Fractions - How We Compare!



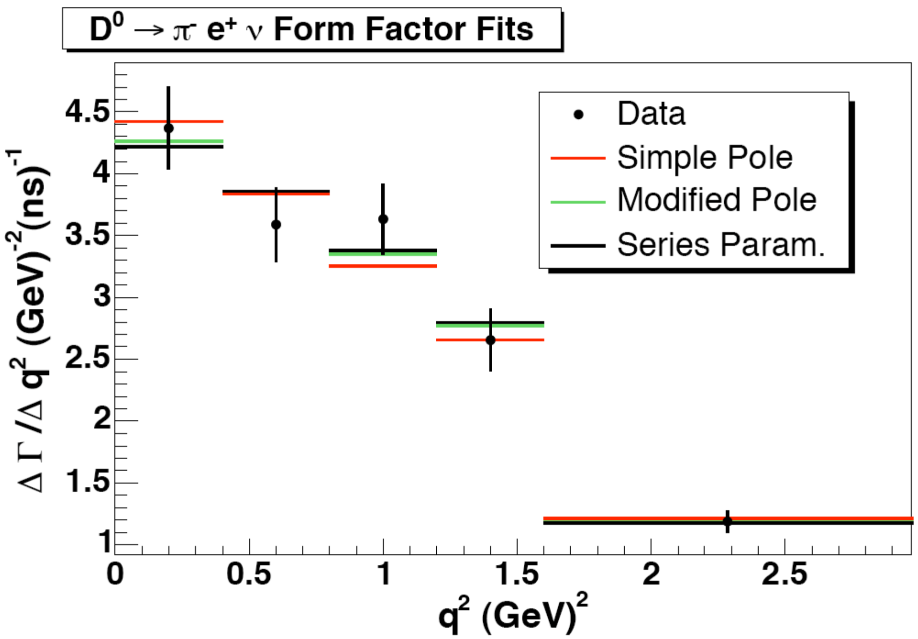
Form Factors

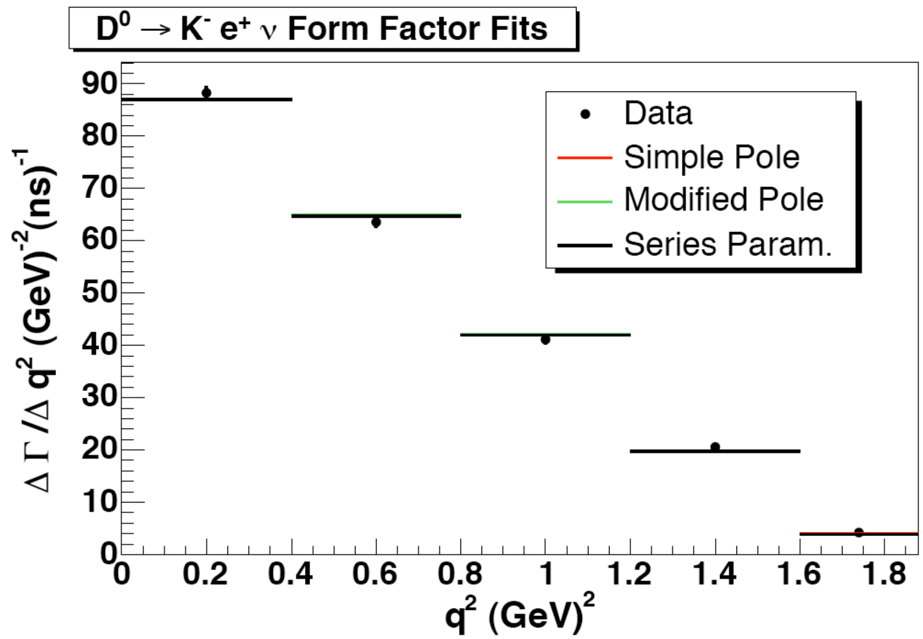
- To obtain form factors we fit our branching fraction results in each q^2 range using:

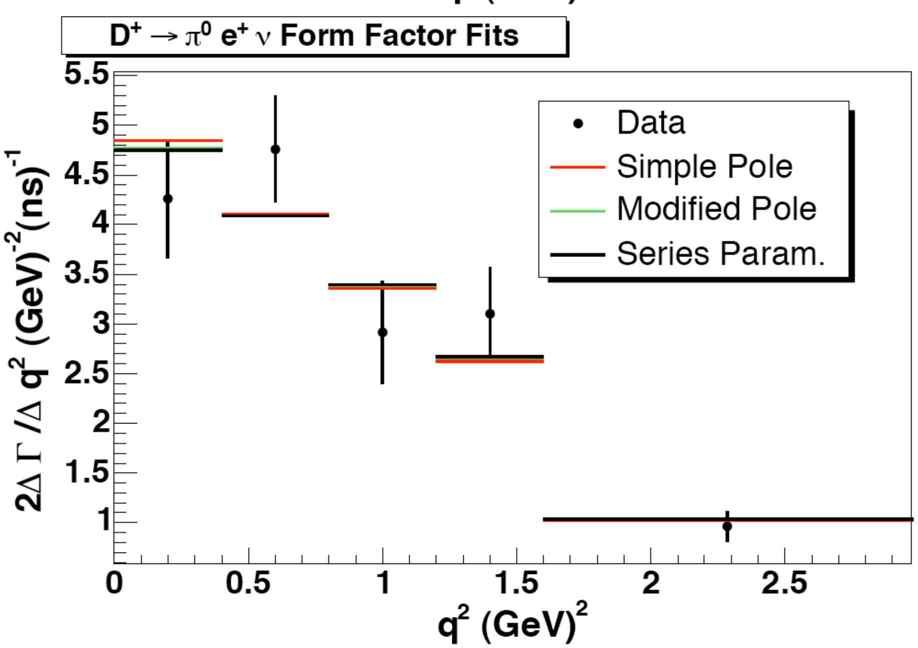
$$B^i_{\pi(K)} = \frac{1}{\Gamma_{Total}} \int_{q^i_{low}}^{q^i_{high}} \frac{G_F^2 \left|V_{cd(s)}\right|^2}{24\pi^3} p^3_{\pi(K)} \left|f_+^{\pi(K)}\left(q^2\right)\right|^2 dq^2$$

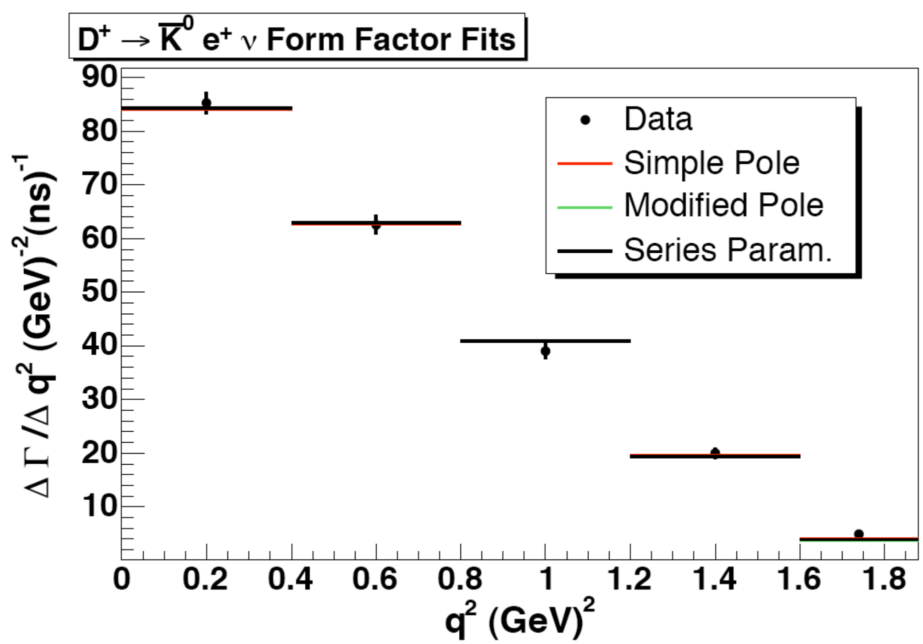
- Where B^i is the measured branching fraction in the i^{th} q^2 bin.
- (Reminder!) We fit three different parameterizations of the form factor
  - Hill & Becher series expansion *(Phys. Lett. B 633, 61 (2006))*
  - Simple Pole Model
  - BK or Modified Pole Model *(Phys. Lett. B 478, 417 (2000))*
- Systematic errors are obtained by running the resulting set of branching fraction central values from each systematic error through the fit and finding the difference.

Form Factor Fit Plots

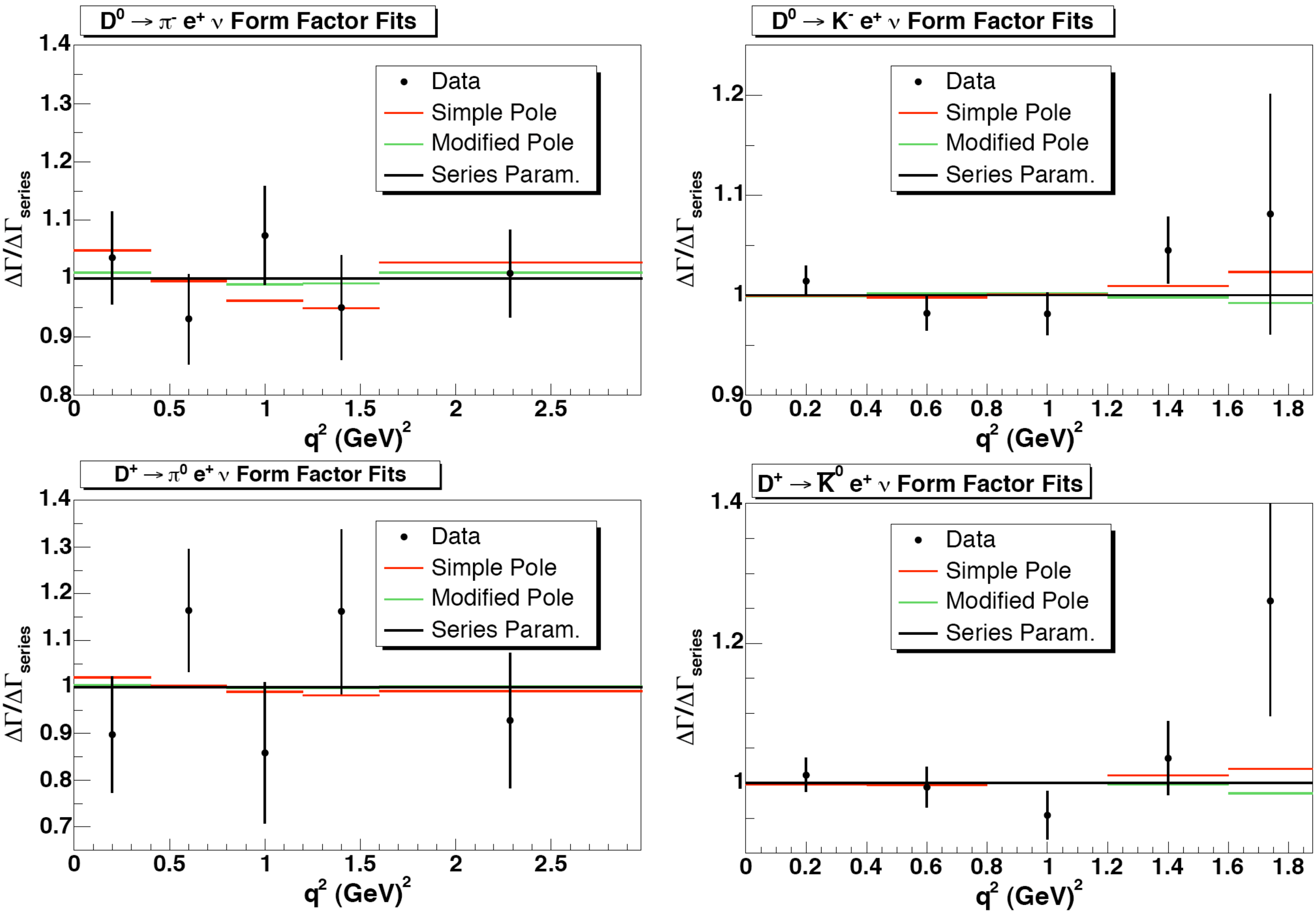








Form Factor Fit Plots - ΔΓ/ΔΓ(series)



Preliminary!

Form Factor Results

Series Parameterization			
Decay Mode	$\lvert V_{cx}\rvert f_+(0)$	$1+1/\beta-\delta$	ρ
$D^0 \to \pi^- e^+ \nu$	$0.140 \pm 0.005 \pm 0.003$	$1.26 \pm 0.09 \pm 0.04$	0.77
$D^0 \to K^- e^+ \nu$	$0.732 \pm 0.006 \pm 0.008$	$0.84 \pm 0.03 \pm 0.02$	0.81
$D^+ \to \pi^0 e^+ \nu$	$0.148 \pm 0.008 \pm 0.004$	$0.99 \pm 0.13 \pm 0.05$	0.73
$D^+ \to \bar{K}^0 e^+ \nu$	$0.712 \pm 0.009 \pm 0.011$	$0.85 \pm 0.05 \pm 0.03$	0.80
Simple Pole Model			
Decay Mode	$\lvert V_{cx}\rvert f_+(0)$	$m_{\rm pole}$	ρ
$D^0 \to \pi^- e^+ \nu$	$0.145 \pm 0.004 \pm 0.002$	$1.87 \pm 0.03 \pm 0.01$	-0.82
$D^0 \to K^- e^+ \nu$	$0.732 \pm 0.005 \pm 0.008$	$1.98 \pm 0.03 \pm 0.02$	-0.83
$D^+ \to \pi^0 e^+ \nu$	$0.150 \pm 0.007 \pm 0.004$	$1.97 \pm 0.07 \pm 0.02$	-0.79
$D^+ \to \bar{K}^0 e^+ \nu$	$0.708 \pm 0.008 \pm 0.010$	$1.97 \pm 0.05 \pm 0.02$	-0.82
Modified Pole Model			
Decay Mode	$\lvert V_{cx}\rvert f_+(0)$	α	ρ
$D^0 \to \pi^- e^+ \nu$	$0.141 \pm 0.004 \pm 0.003$	$0.37 \pm 0.09 \pm 0.03$	0.71
$D^0 \to K^- e^+ \nu$	$0.731 \pm 0.006 \pm 0.008$	$0.19 \pm 0.05 \pm 0.03$	0.78
$D^+ \to \pi^0 e^+ \nu$	$0.148 \pm 0.008 \pm 0.004$	$0.12 \pm 0.17 \pm 0.05$	0.68
$D^+ \to \bar{K}^0 e^+ \nu$	$0.707 \pm 0.009 \pm 0.011$	$0.20 \pm 0.08 \pm 0.04$	0.78

$$\frac{(M_D^2 - m^2)}{f_+(0)} \left.\frac{df_+}{dq^2}\right|_{q^2=0} \approx 2$$

These models are not physically meaningful!

Preliminary!

Shape Comparison - Experiment

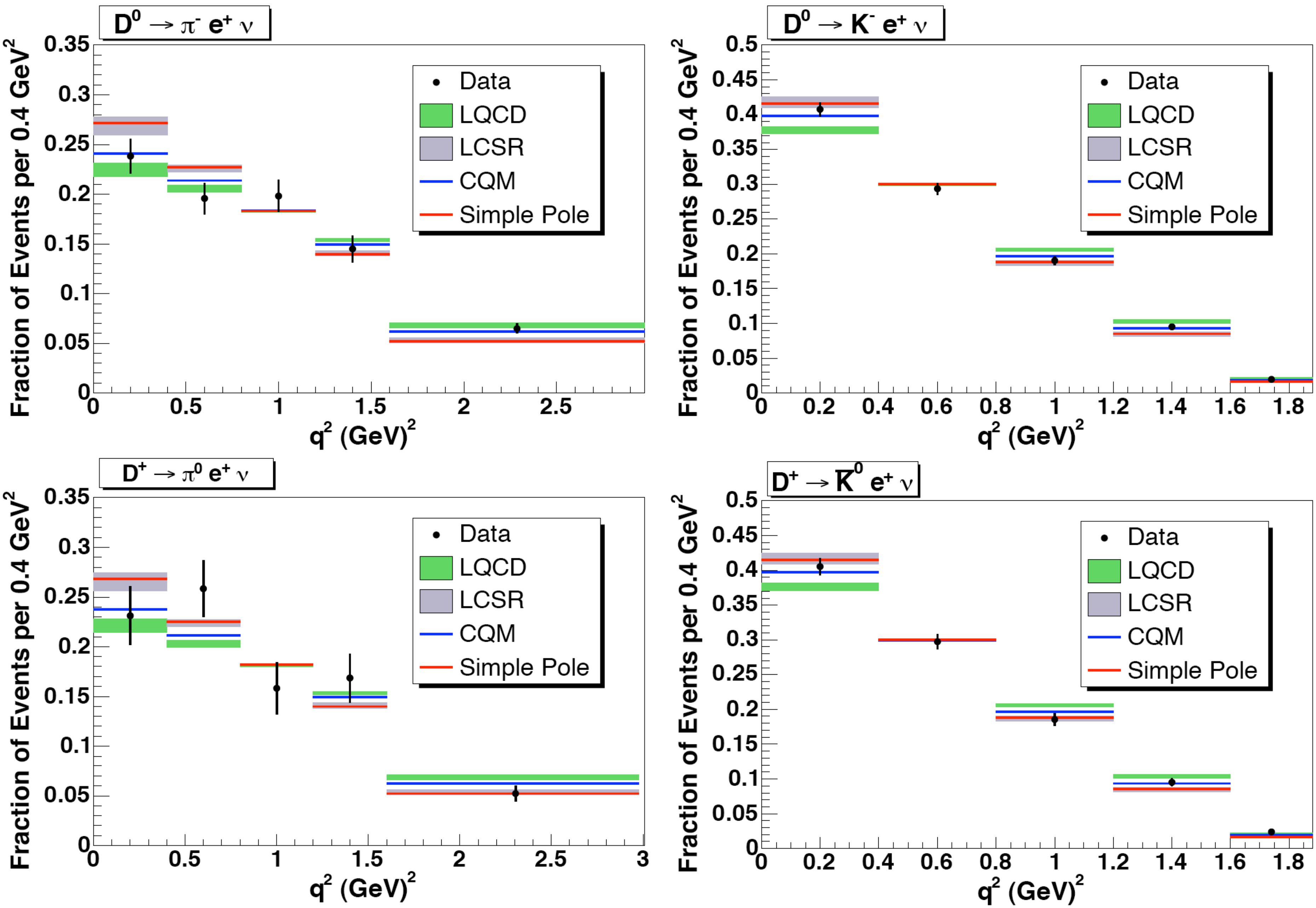
$D \to K$

	Shape Parameter	
Measurement	α	$m_{\rm pole}$ GeV
E691 1989	-	$2.1^{+0.4}_{-0.2} \pm 0.2$
CLEO 1991	-	$2.0^{+0.4+0.3}_{-0.2-0.2}$
MarkIII 1991	-	$1.8^{+0.5+0.3}_{-0.2-0.2}$
CLEOII 1993	-	$2.00 \pm 0.12 \pm 0.18$
E687 1995	-	$1.87^{+0.11+0.07}_{-0.08-0.06}$
CLEOIII 2005	$0.36 \pm 0.10^{+0.03}_{-0.07}$	$1.89 \pm 0.05^{+0.04}_{-0.02}$
FOCUS 2005	$0.28 \pm 0.08 \pm 0.07$	$1.93 \pm 0.05 \pm 0.03$
Belle 2006	$0.40 \pm 0.12 \pm 0.09$	-
Babar 2006	$0.43 \pm 0.03 \pm 0.04$	$1.854 \pm 0.016 \pm 0.020$
CLEO-c 2006 D^0	$0.19 \pm 0.05 \pm 0.03$	$1.98 \pm 0.03 \pm 0.02$
CLEO-c 2006 D^+	$0.20 \pm 0.08 \pm 0.04$	$1.97 \pm 0.05 \pm 0.02$

$D \to \pi$

	Shape Parameter	
Measurement	α	$m_{\rm pole}$ GeV
CLEOIII 2005	$0.37^{+0.20}_{-0.31} \pm 0.15$	$1.86^{+0.10+0.07}_{-0.06-0.03}$
FOCUS 2005	-	$1.91^{+0.30}_{-0.15} \pm 0.07$
Belle 2006	$0.10 \pm 0.21 \pm 0.10$	-
CLEO-c 2006 D^0	$0.37 \pm 0.09 \pm 0.03$	$1.87 \pm 0.03 \pm 0.01$
CLEO-c 2006 D^+	$0.12 \pm 0.17 \pm 0.05$	$1.97 \pm 0.07 \pm 0.02$

Shape Comparison - Theory



Preliminary!

V_{cs} and V_{cd} (Preliminary)

- To calculate preliminary values for V_{cs} and V_{cd} we use our measured values of $|V_{cx}|f(0)$ together with lattice QCD results for $f(0)$ (*Phys. Rev. Lett. 94, 011601 (2005), hep-lat/0409116*).
- For our final results this will be done with a more sophisticated fitting method.

Decay Mode	$\lvert V_{cx}\rvert \pm (stat) \pm (syst) \pm (theory)$	*PDG/HF Value*
$D^0 \to \pi^\pm e\nu$	0.222 ± 0.012 ± 0.005 ± 0.028	0.224 ± 0.012
$D^\pm \to \pi^0 e\nu$	0.236 ± 0.016 ± 0.007 ± 0.029	
$D^0 \to K^\pm e\nu$	1.005 ± 0.042 ± 0.014 ± 0.103	0.976 ± 0.014
$D^\pm \to K^0 e\nu$	0.986 ± 0.043 ± 0.018 ± 0.101	

Summary

- Measured branching fractions and branching fraction ratios in five q^2 ranges.
- Fit branching fraction spectra to Becher & Hill series parameterization as well as pole models for comparison.
- Extracted preliminary V_{cs} and V_{cd} results using lattice QCD values.

Prospects for CLEO-c!

CLEO-c aims to take a total of ***750/pb*** *at the ψ(3770)*
Many measurements will be further improved!

CKM measurements improve experimental errors! Lattice error contributions (not shown) should also be down 10% → < 3%.

$$V_{cd} = 0.222 \pm 0.012 \pm 0.005 \longrightarrow V_{cd} = 0.222 \pm 0.007 \pm 0.003$$

$$V_{cs} = 1.005 \pm 0.042 \pm 0.014 \longrightarrow V_{cs} = 1.005 \pm 0.026 \pm 0.009$$

Remember we can also look at leptonic to semileptonic ratios. These will improve with more statistics: ***$D^+ \to \mu^+\nu$ is statistics limited!***

$$\frac{\Gamma\left(D^+ \to \mu^+\nu_\mu\right)}{\Gamma\left(D^+ \to \pi^0 e^+\nu\right)} = 0.11 \pm 0.02$$

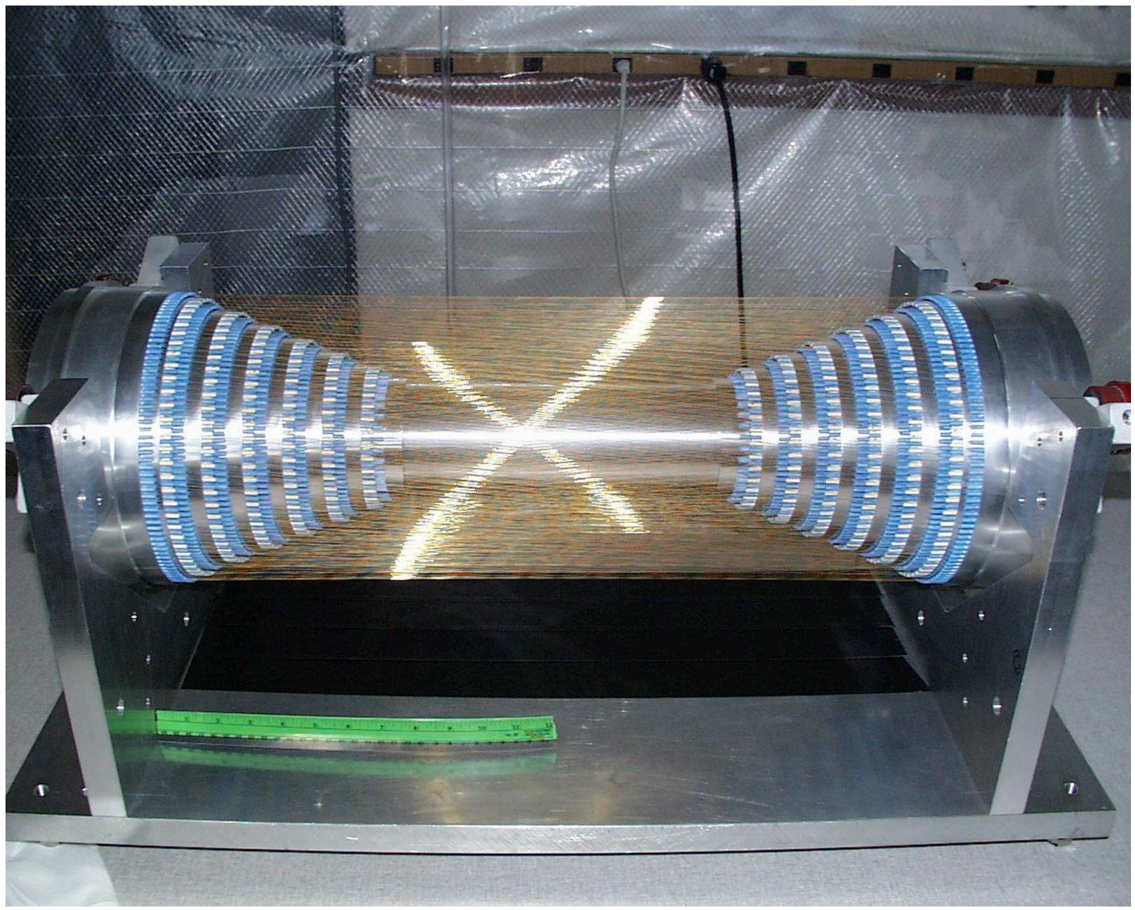
17% → 10% error

$$\frac{\Gamma\left(D^+ \to \mu^+\nu_\mu\right)}{\Gamma\left(D^0 \to \pi^- e^+\nu\right)} = 0.058 \pm 0.009$$

16% → 10% error

Backup Slides!

More ZD!



CKM Matrix

$$\begin{pmatrix} 0.9739-0.9751 & 0.221-0.227 & \boxed{0.0029-0.0045} \\ \boxed{0.221-0.227 \quad 0.9730-0.9744} & & \boxed{0.039-0.044} \\ 0.0048-0.0014 & 0.037-0.043 & 0.9990-0.9992 \end{pmatrix}$$

CKM matrix at 90% confidence (PDG 2005)